PRINCIPLES OF
WIRELESS TELEGRAPHY

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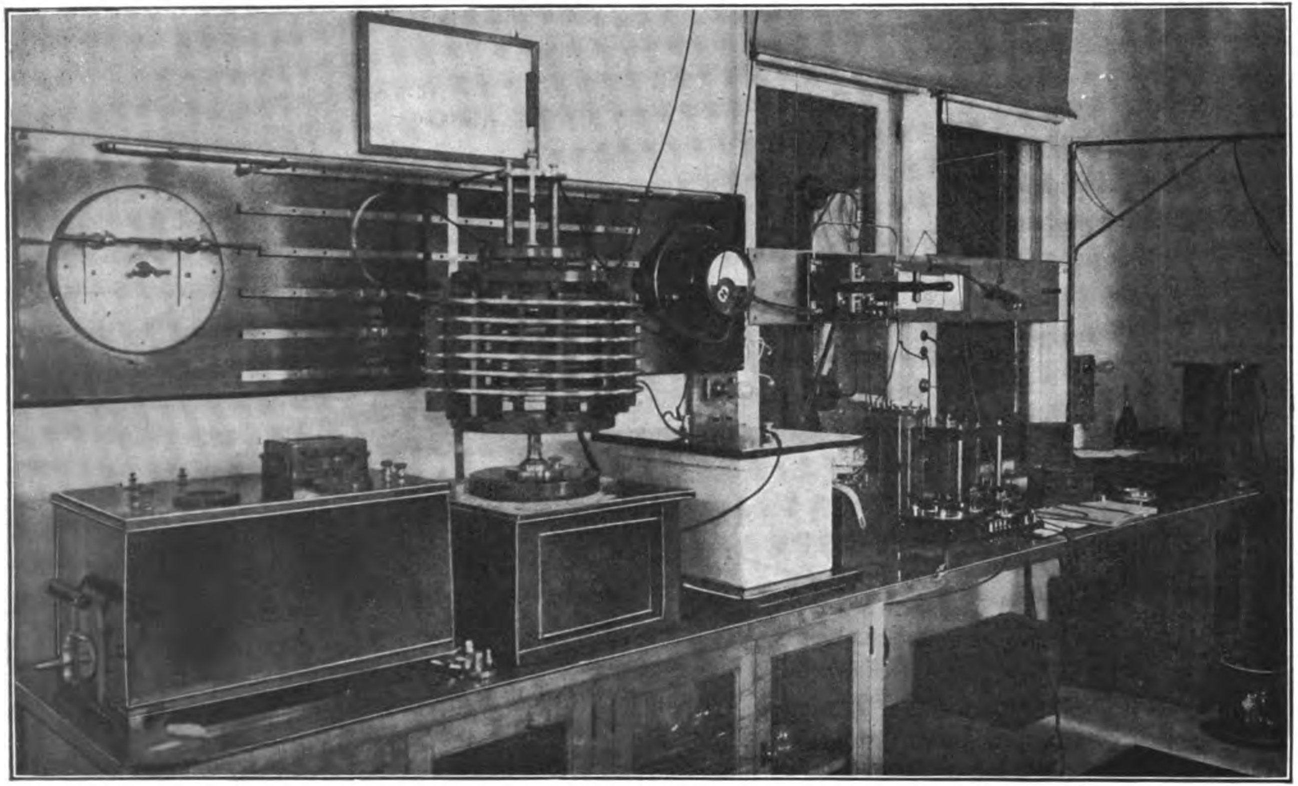

Frontispiece Wireless telegraph station of Mr. Elliott Woods, Washington, D. C.

PREFACE

THIS volume comprises the non-mathematical portions of a course of lectures, entitled "Electric Waves and their Application to Wireless Telegraphy," which for several years have been given by the author to classes at Harvard University. In giving the lectures and in preparing this volume, the design has been: — First, to present, in as elementary a form as possible, the course of reasoning and experimentation that has led to the conception of electric waves; second, to follow this with a discussion of the properties of electric waves and electric oscillations; third, to give a history of the application of electric waves to wireless telegraphy; and fourth, to elaborate the general principles and methods of electric-wave telegraphy in sufficient detail to be of possible use to elementary students of electricity and to amateur and professional electricians engaged in operating and constructing wireless telegraphic apparatus.

The author wishes to express his sincere thanks to Commander S. S. Robison of the United States Navy, to Mr. Elliott Woods of Washington, and to Chief Inspector D. M. Mahood of the New York Navy Yard for their kindness in supplying photographs for some of the illustrations. Also, the author is grateful to the Editors of the *Physical Review* for the loan of Plates I and II, and to Mr. Greenleaf Whittier Pickard for the privilege of consulting his manuscript account of experiments on the effects of daylight on transmission. Finally, the author takes great pleasure in expressing his gratitude to his friend Mr. George Francis Arnold, who has kindly read the proofs and made many valuable suggestions.

G. W. PIERCE.

HARVARD UNIVERSITY, CAMBRIDGE, MASS.
July, 1910.

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CHAPTER I

INTRODUCTION

Almost every one has seen and heard the noisy, brilliant spark produced by the discharge of a Leyden jar. The experiment, shown in elementary courses in physics, is usually performed as follows: The inner and outer coatings of the Leyden jar are connected to the terminals of a static electric machine. The machine is set in rotation and the jar is charged. After the jar has been charged, the electric machine is disconnected, and one end of a metallic rod, held by an insulated handle (see Fig. 1), is touched against the outer coating of the jar, while the other end of the rod is made to approach a knob connected with the inner coating. Before the conductor to the inner coating is actually touched, a discharge occurs through the metallic rod, producing a vivid spark at the gap intervening between the knob and the discharge rod. As a variation of the experiment, in the place of the straight or slightly curved metallic rod used in the discharge apparatus of Fig. 1, a coil consisting of a few turns of heavy wire may

Fig. 1. Leyden jar and discharger.

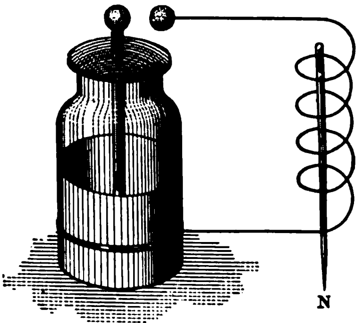

Fig. 2. Leyden jar with coil in discharge circuit.

be employed to form a part of the circuit between the two coatings of the jar, as is shown in Fig. 2.

The flow of electricity in a circuit of the form of Fig. 1 or Fig. 2 has been the subject of many interesting theoretical and experimental investigations directly applicable to the subject under consideration.

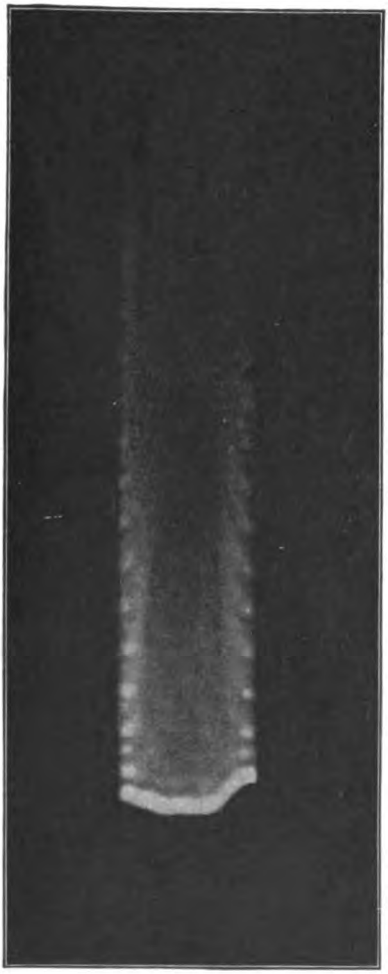

FIG. 3. Rotating-mirror photograph of oscillatory discharge.

The Experiments of Joseph Henry. — Some experiments performed by Professor Joseph Henry[1] of Princeton University in the year 1842 gave intimation that, under certain conditions, the discharge of the Leyden jar takes place in an oscillatory fashion. Let us give a brief description of Henry's experiment. A small sewing needle was placed within the coil of wire of the discharge circuit, as is shown at *N*, Fig. 2, so that the electricity from the Leyden jar was made to flow in the coil around the needle. At the time of Henry's experiment it was already well known that a current of electricity from an ordinary galvanic battery, when caused to flow in a coil of wire encircling a steel needle, magnetizes the needle. Henry's experiment showed that the current of electricity from the Leyden jar also produced magnetization of the needle. It was partly in search of this fact, showing the identity of static and galvanic electricity, that Henry's experiment was undertaken. In the experiment, however, Henry discovered the additional fact, that with

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[1] See Scientific Writings of Jos. Henry, Vol. I, p. 201, Washington, 1886.

the Leyden jar always charged in the same direction by the electric machine used to charge the jar, the needle was sometimes found to be magnetized in one direction and sometimes in the opposite direction, indicating that the current that produced the magnetization of the needle was flowing in the coil in the one case from the outside of the jar towards the inner coating, while in the other case it was flowing from the inner coating to the outer coating. This effect could be explained by supposing that the current from the Leyden jar was oscillatory, having first one direction and then the other, and that the magnetization of the needle was reversed at each reversal of the current, the direction of the magnetization at the end of the experiment being fortuitously determined by the direction last taken by the current. Professor Henry's experiment, though not conclusive, gave strong evidence of the oscillatory character of the discharge; and the opinion that the discharge is oscillatory was repeatedly expressed and defended by Professor Henry in a number of papers and scientific addresses delivered between 1842 and 1850.

Sir William Thomson's Theoretical Proof of the Oscillatory Nature of the Discharge of the Leyden Jar. — In 1853 Sir William Thomson,[1] who was afterwards Lord Kelvin, proved by mathematical reasoning that under certain conditions the discharge of a Leyden jar occurs in an oscillatory manner. Under certain other conditions the discharge is non-oscillatory. In the case of the oscillatory discharge the electricity does not simply flow from one coating to the other until the jar is in a condition of electric neutrality, but rushes back and forth between the two coatings a great number of times, with a frequency depending on the dimensions of the jar and the dimensions and form of the coil through which the discharge occurs.

Feddersen's Revolving-Mirror Experiment. — In 1859 Doctor Feddersen of the University of Leipzig, by a very beautiful experiment, proved the correctness of the surmise of Henry and the mathematical predictions of Thomson. Feddersen's experiment consisted in photographing the spark produced by the discharge of the Leyden jar. A photograph similar to that obtained by Feddersen is shown in Fig. 3. A sketch of the apparatus used in taking the picture is shown in Fig. 4. Instead of employing an ordinary camera to take the picture, the light from the spark *S*, produced by the discharge of the jar, was allowed to fall upon

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[1] Wm. Thomson: Philosophical Magazine [4], 5, p. 393, 1853.

a rapidly revolving concave mirror *M* of Fig. 4, and was received upon a photographic plate *P* after reflection from the mirror. Just as the light of a sunbeam entering a room may be reflected upon the wall or ceiling of the room by a mirror held in the hand, and may be made to move rapidly up the wall or across the ceiling by a rotation of the mirror, so in Feddersen's experiment the motion of the mirror caused the image of the spark to trail rapidly across the photographic plate. If the spark had been steady and unidirectional, the image on the plate would have been simply a band of light with a length depending on the speed of the mirror and the duration of the spark. The picture (compare Fig. 3) shows, on the contrary, that the conditions at the spark reversed several times during the discharge, so that first one terminal of the spark was bright and then the other, — the bright terminal being evidenced by the bright spots on the photograph of Fig. 3. The successive alterations of the bright spots from one side to the other of the photograph showed the successive reversals of the current across the spark gap during the discharge.

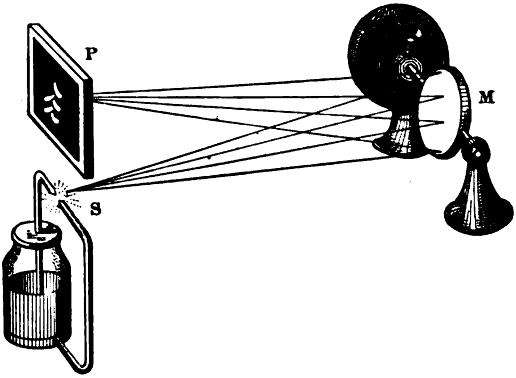

Fig. 4. Rotating mirror apparatus.

Feddersen's photographs proved beyond doubt the correctness of Thomson's prediction of the oscillatory nature of the discharge, and gave, as we shall see later, a very beautiful method of measuring the periodic time of oscillation of the discharge, — a time which may be only a small fraction of a millionth of a second, and which is yet subject to accurate physical measurement.

It is by means of electric oscillations similar to those produced by the Leyden-jar discharge that wireless telegraph signals are produced.

Electric Waves. Maxwell's Theory. — In a letter to C. H. Cay, Esq., dated 5th of January, 1865, James Clerk Maxwell, then Professor of Physics in the University of Edinburgh, wrote:

"I have also a paper afloat with an electromagnetic theory of light, which till I am convinced to the contrary, I hold to be great guns."

This paper to which Maxwell referred contained a prediction, based on careful mathematical reasoning, that electric oscillations in a circuit produce electric waves in surrounding space, that these waves travel away with the velocity of light, and that light itself is simply a train of electric waves of extremely short wave length. This prediction of Maxwell, correlating the phenomena of light and electricity, is one of the most beautiful philosophic speculations in the history of science, and long remained without direct experimental confirmation; but now, thanks to the brilliant experiments of Heinrich Hertz, the existence of electric waves with properties intimately related to those of light waves is a well-established fact of experience capable of verification in even very elementary physical laboratories.

It is by means of these electric waves that the signals of wireless telegraphy and telephony are propagated through space.

In the succeeding chapters, we shall take up more in detail the course of reasoning that led to Thomson's and Maxwell's predictions, the course of experimenting that led to the proofs of the existence of their electric oscillations and electric waves, and the development of the very striking methods that have been employed in utilizing these electric oscillations and electric waves in the transmission of signals. The discussion will introduce some details apparently remote from commercial usefulness; but it should be borne in mind that it has been by means of persistent and laborious study of these details that the practical result has been attained.

CHAPTER II

ON THEORIES AS TO THE NATURE OF ELECTRICITY

In the preceding chapter mention has been made of the oscillatory flow of electricity back and forth between the two coatings of a Leyden jar, when the jar is allowed to discharge through a conductor. The description there given of the "flow of electricity" will probably call to the mind of the reader a picture of a motion back and forth of some kind of material substance from one reservoir to another. At the same time, it may be difficult to imagine the flow of any kind of substance through the solid metal of which the conductor is composed. What then is this electricity that can flow through solid conductors?

This is a question that we cannot hope to answer to our complete satisfaction, but we have recently come to have so much light thrown upon the question that it is proposed to devote a few pages to the discussion of theories as to the nature of electricity.

In the works of the early writers on electricity two prominent hypotheses have been made as to the nature of electricity. These have been called the *two-fluid theory* and the *one-fluid theory*. The chief facts that these theories were at first called upon to explain were:

(1) The phenomenon of electrostatic attraction and repulsion; for example, the attraction or repulsion between two charged pith balls, and

(2) The fact that when electrification was produced in any way two opposite charges were always obtained; for example, when a glass rod is rubbed with silk, a certain quantity of positive electricity appears on the glass rod and an equal quantity of negative electricity appears on the silk.

THE TWO-FLUID THEORY

According to the two-fluid theory all bodies in their unelectrified condition were supposed to contain equal quantities of two subtle fluids, one of which was called positive electricity, and the other negative electricity. On this theory the process of positively electrifying a body consists in adding to it a quantity of the positive fluid or taking from it a quantity of the negative fluid. The state of electrification of a body is hence determined by the *excess* in amount of one of the fluids over the other. In order to account for the fact that the appearance of electrification of one sign is always accompanied by the appearance of an equal amount of electrification of the opposite sign, the two fluids were supposed to be uncreatable and indestructible, so that the accumulation of positive electricity in one body is always accompanied by the loss of positive electricity in some other body. This is the principal property that the electrical fluids were supposed to have in common with ordinary material fluids; namely, *the property of conservatism in amount* according to which *the total amount of electricity in a given system can only be changed by the transfer of electricity through the boundary of the system.*

The electrical fluids, on the other hand, must possess properties that do not belong to the material fluids; for example, portions of the positive fluid must be supposed to repel each other, as do also portions of the negative fluid, while the two unlike fluids attract each other. Another property of the electrical fluids still more at variance with the known properties of material fluids is found in the fact that if we add equal quantities of the two electrical fluids to the same body, the condition of the body will be unchanged, so that according to this theory we must suppose that "the mixture of the two fluids in equal proportions is something so devoid of physical properties that its existence has never been detected."[1]

THE ONE-FLUID THEORY

Benjamin Franklin attempted to describe the phenomena of electricity in terms of a single fluid. According to his theory, one of the fluids, the positive, was retained and called *the electric fluid,* while the other, the negative fluid of the two-fluid theory, was replaced by ordinary matter. Quantities of the electric fluid were supposed to repel other quantities of the fluid according to the law of the inverse square of the distance and to attract matter according to the same law. Quantities of matter were supposed to repel each other and attract the electric fluid. According to Franklin's theory an excess of the electric fluid rendered the body positive, while a deficiency rendered it negative.

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[1] J. J. Thomson, Electricity and Matter, Charles Scribner's Sons, 1904.

THE ATOMIC STRUCTURE OF ELECTRICITY

Both of the theories sketched above are useful in supplying a terminology for electricity and in affording a simple mode of presentation of some of the phenomena, but both theories are characterized by indefiniteness as to the physical properties of electricity.

Recently, however, a number of phenomena have been studied that have led to a somewhat bolder statement as to the nature of electricity. In accordance with data obtained chiefly from the study of the conduction of electricity by liquids and gases, electricity is now generally supposed to have a structure that may be called *atomic*.

The first evidence pointing in this direction was obtained by Faraday in the course of a research on the conduction of electricity by decomposable liquids. When an electric current is passed through water, the water is decomposed into hydrogen, given off at one electrode, and oxygen, given off at the other. A great many other liquids — for example, the aqueous solutions of various salts — are similarly decomposed by the action of the current. An electrically decomposable liquid is called by Faraday an Electrolyte. Faraday discovered the following laws of electrolytic decomposition.

I. In a given electrolyte, the amount of substance decomposed by various electric currents is proportional to the quantity of electricity sent through the electrolytes.

II. If the same amount of electricity is sent through various electrolytes, the amount of the several decomposition products obtained from the various electrolytes is proportional to the combining weights of the products obtained. For example, if hydrogen (2 H) and Oxygen (O) are obtained in one electrolytic cell, and silver (Ag) and chlorine (Cl) in another cell, the amounts of these various substances obtained, when a given electric current is sent through both cells, are in the ratio of their chemical combining weights.

According to the atomic theory of matter, these two laws may be interpreted by supposing that each of the decomposition products carries a charge that is an integral multiple of the charge carried by the hydrogen atom; so that, if the hydrogen atom, in the process of carrying a current electrolytically, is supposed to have associated with it a definite small quantity of electricity, any combination of atoms, when carrying a current, have associated with them an equal small quantity of electricity or an integral multiple thereof. That is, the charges we meet with are never fractional parts of the charge carried by the hydrogen atom; whence we may suppose that the latter charge is an elemental quantity of electricity. In discussing the evidence afforded by Faraday's experiments Helmholtz[1] says that "if we accept the hypothesis that the elementary substances are composed of atoms, we cannot avoid the conclusion that electricity, positive as well as negative, is divided into definite elementary portions which behave like atoms of electricity."

The study of the conduction of electricity through gases gives still stronger evidence of the atomic character of electricity. Gases under the action of certain agencies — Roentgen rays, ultra-violet light, radium, high electromotive forces, electric spark, etc. — become conductive and retain their conductivity long enough to permit a study of the mechanism by which the electricity is conducted. As in the case of the study of conduction in liquids, we are again "led to the conception of a natural unit or atom of electricity of which all charges are integral multiples, just as the mass of a quantity of hydrogen is an integral multiple of the mass of a hydrogen atom."[2]

By the study of conduction in gases definite information is obtained in regard to the magnitude of this charge. In a series of experiments performed chiefly at the Cavendish Laboratory of Cambridge University the quantity of electricity in one electrical atom is found to be 3.4×10^{-10} electrostatic c. g. s. units.[3] This quantity obtained from experiments on conduction in gases is the same as the quantity of electricity carried by one hydrogen atom in the electrolysis of liquids.

Mass of the Carriers of Electricity. — Also at the Cavendish Laboratory evidence as to the mass of the carriers of electricity has been obtained by an experimental determination of the ratio of e/m, in which e is the elemental charge and m is the mass of matter carrying the charge. The result obtained is that the mass of the carrier, *when the electricity is negative*, is about 1/1700 of the mass of the hydrogen atom. This mass is apparently the same

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[1] J. J. Thomson, Electricity and Matter, p. 73, Charles Scribner's Sons, 1904.

[2] J. J. Thomson, Electricity and Matter, p. 83, Charles Scribner's Sons, 1904.

[3] The electrical units are defined in Appendix I.

whatever the nature of the gas in which the particle happens to be found. While the mass of the carrier of *positive electricity* is approximately the mass of the atom of ordinary matter, and apparently differs from one gas to another in the same way as the atoms of the gas differ. J. J. Thomson proposes the name " corpuscle " for the unit of negative electricity, and sums up the corpuscular theory of electricity as follows:

" These results lead to a view of electrification which has a striking resemblance to that of Franklin's *One-Fluid Theory of Electricity*. Instead of taking, as Franklin did, the electric fluid to be positive we take it to be negative. The *Electric Fluid* of Franklin corresponds to an assemblage of corpuscles, negative electrification being a collection of these corpuscles. The transference of electrification from one place to another is effected by the motion of corpuscles from the place where there is a gain of positive electrification to the place where there is a gain of negative. A positively electrified body is one that has lost some of its corpuscles. We have seen that the mass and the charge of the corpuscles have been determined directly by experiment. We in fact know more about the *electric fluid* than we know about such fluids as air and water." [1]

In applying Thomson's Theory to the flow of electricity in conductors we must suppose that these small charged bodies, with a mass equal to about 1/1700 of the mass of the hydrogen atom, are able under the action of electric forces to move through the substance of even such solid conductors as the metals, and that a stream of these small charged bodies constitutes or carries the electric current. We must, however, bear in mind that the stream of negative particles is in the opposite direction to the direction conventionally ascribed to the electric current.

If we wish now to picture to ourselves the flow of electricity in the Leyden-jar discharge, we may think of a stream of these small negatively charged corpuscles passing from the outer coating of the jar through the discharge rod and across the spark gap and accumulating on the inner coating. This charges the inner coating negatively and leaves the outer coating deficient in corpuscles and therefore charged positively. The stream of corpuscles then reverses, flows from the inner coating to the outer, and reverses the charge on the jar. This process continues, each time with a loss

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[1] J. J. Thomson, Electricity and Matter, p. 88, Charles Scribner's Sons, 1904.

of electromotive force, until the electric tension finally becomes too small to force the corpuscles across the spark gap.

This description is given merely so that the reader may picture an electric current to his mind. The question as to how and why the discharge of the Leyden jar oscillates will be discussed later, after some more of the elementary facts about electric currents have been presented.

CHAPTER III

ON THE RELATION BETWEEN ELECTRICITY AND MAGNETISM

In the preceding chapter I have given some of the newest speculations in regard to the nature of electricity. The particular views there expressed are not essential to the development of the conception of electric oscillations and electric waves, so that the reader may be skeptical about the atomic structure of electricity and still be able to follow the arguments for Maxwell's Theory. In the present chapter I wish to return to surer ground, and give some of the older experiments on electricity and magnetism and on the relation of electricity to magnetism.

Prior to 1820 the phenomena of electricity and magnetism were not known to be related to each other. The familiar facts about magnetism were: that there is a mineral called *loadstone* that has the power of attracting pieces of iron; that a piece of soft iron brought near the loadstone becomes also a magnet with the power to attract iron, but only temporarily, for the piece of soft iron loses most of its magnetism when it is removed to a distance from the loadstone; while a piece of hardened steel brought near the loadstone or another magnet becomes a so-called *permanent magnet,* and retains a considerable part of its magnetism even when at a great distance from the loadstone. It was also known that a steel needle, magnetized by rubbing it on a loadstone or another magnet, and pivoted so as to be free to rotate in a horizontal plane, points in approximately a north and south direction.

About electricity it was known that amber, glass and sealing wax were capable of being electrified by rubbing them with silk, flannel, fur, etc.; that the electrifications so produced were of two kinds, positive and negative; that unlike charges attract each other and like charges repel; that these positive and negative charges could be stored in an apparatus of the form of a Leyden jar; that certain bodies, such as metals, carbon, water and so forth, were conductors of electricity, so that the electricity would flow freely through such bodies. Also the galvanic cell was known, and was employed to produce a continuous flow of electricity in wires. This continuous flow of electricity in a wire or other conductor is an electric current, and was known to produce heating of the conductor through which it flows.

In 1820 a new impetus was given to a study of electricity and magnetism by the discovery by Hans Christian Oersted of Copenhagen that magnetism and electricity are interrelated. This discovery and some of its consequences is described in the succeeding paragraphs.

On the Production of a Magnetic Field by a Current of Electricity. — Oersted's discovery was nothing less than the important fact that when a pivoted magnetic needle is placed near a wire carrying a current of electricity, the magnetic needle tends to set itself at right angles to the wire which carries the electric current. If the current is reversed, the direction of the deflection of the magnetic needle is reversed. If the wire carrying the current is moved from a position below the needle to a position above the needle, the deflection of the needle is again reversed.

Oersted's discovery has been utilized in the construction of the galvanometer, which is a very delicate instrument for detecting and measuring small electric currents. The principle of the galvanometer is as follows: A magnetic needle pivoted as in the ordinary compass, so as to be free to move in a horizontal plane, will, if undisturbed, take up a position in the magnetic meridian of the earth; that is, the needle will point approximately north and south, (M, Fig. 5). Suppose, now, that a wire is passed alternately above and below the needle several times so as to form a coil (C, Fig. 5), with its windings in the plane of the magnetic meridian. Let a current be passed through the coil, so as to flow north above the needle and south below it; the north current above the needle and the south current below it both tend to deflect the north-seeking end of the magnetic needle to the west, so that the effect of the current on the needle is multiplied by the combined action of the several turns of the conductor around the needle. For a highly sensitive galvanometer, the magnetic needle instead of being pivoted is delicately suspended by a fine fiber of spun quartz.

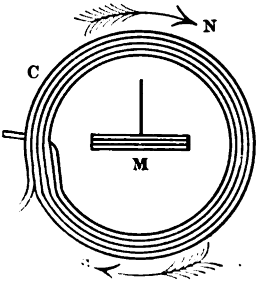

Fig. 5. Coil and needle of galvanometer.

In addition to its application to the construction of the galvanometer, Oersted's principle is utilized in the construction of almost every kind of electromagnetic device.

Interpretation of Oersted's Experiment. — The results of Oersted's experiment are now usually expressed by saying *that a current of electricity in a conductor produces a field of magnetic force in the neighborhood of the conductor.* In explanation of this statement the reader is asked to recall the familiar experiment in which a sheet of paper laid upon a bar magnet is covered with iron filings. The filings become magnetized and arrange themselves in curved lines stretching from one pole of the magnet to the other, as shown in Fig. 6. The direction of these lines traced by the filings is approximately the direction of the *magnetic force* about the magnet. These lines, delineated by the filings, are the lines along which a small suspended magnetic needle would orient itself if brought near the bar magnet.

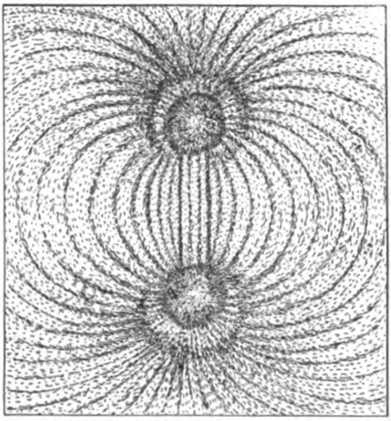

FIG. 6. Magnetic field about a bar magnet, as depicted by iron filings.

The region in which such a magnetic force exists is called a *field of magnetic force.* A piece of unmagnetized steel when placed in such a field becomes magnetized, and retains some of its magnetism even after it is removed from the field of magnetic force.

To show the form of the field of magnetic force about a wire carrying a current, as in Oersted's experiment, iron filings may also be used with the results given in Figs. 7, 8, and 9. Figure 7 is obtained with a straight conductor running perpendicular to the plane of the paper on which the filings are disposed. The picture shows that when a current of electricity is sent through the straight conductor the lines of magnetic force are circles about the conductor. The magnetic force is stronger near the conductor and weaker at a distance from the conductor. Figure 8 is obtained with a coil of a few turns of wire. Figure 9 shows the magnetic field produced by a long helical coil called a *solenoid.* With the solenoid the field of magnetic force is seen to be remarkably like that obtained with the bar magnet.

It may be observed that in the case of each of the coils the lines of magnetic force depicted by the filings interlink with the electric current.

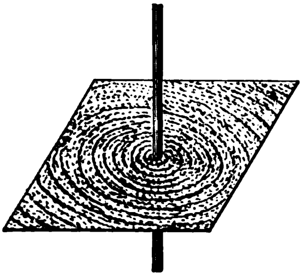

FIG. 7. Magnetic field about a straight conductor carrying an electric current.

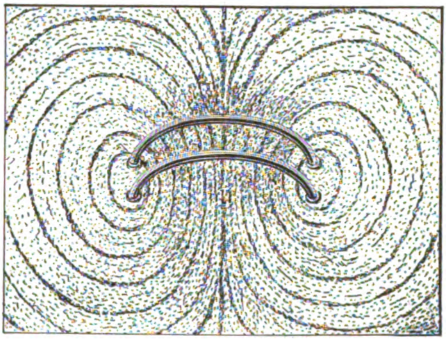

FIG. 8. Magnetic field linking with a coil of two turns carrying a current.

This conception of a field of magnetic force about a conductor carrying an electric current is of fundamental importance in the study of electric waves, in which the action in the medium rather than the action in the wires is the chief factor to be reckoned with.

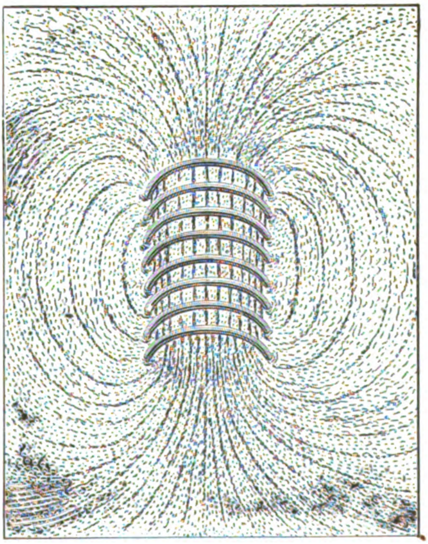

FIG. 9. Magnetic field produced by a solenoid.

So long as the electric current in the conductor remains steady, the magnetic field remains steady. With changes in the electric current, the magnetic field changes. This changing magnetic field about a conductor carrying an oscillatory current will later be shown to be one of the components of the electric waves produced at the sending station of a wireless telegraph system.

On the Production of an Electric Current by a Variation of the Magnetic Field. — Bearing in mind that an electric current produces a field of magnetic force about it, let us turn now to the question *whether an electric current can be produced by the action of a magnetic field.*

For a period of ten years succeeding Oersted's discovery, experiments directed to this question gave the answer in the negative. Finally, in 1831, Faraday in England and Joseph Henry in America succeeded, almost simultaneously, in obtaining electric currents by the action of a magnetic field, and in explaining the cause of previous failures. Faraday and Henry showed that an electric current in a conductor in a magnetic field is obtained as the result of a *change in the magnetic field,* whereas the previous experiments had sought to produce the effect by the magnetic field in a steady state.

One way of producing the required change of magnetic field in the neighborhood of the electric circuit is by the motion of a permanent magnet, with its accompanying field, toward or away from the circuit. This was done in some of Faraday's and Henry's experiments and is here described with the aid of. Fig. 10. A coil of wire C is connected to a galvanometer G. When the north pole of the magnet NS is made to approach and enter the coil C, the needle of the galvanometer is deflected, showing that an electric current is produced. The current is, however, only transient, and after the magnet NS has arrived at its final position and ceased to move, the needle of the galvanometer comes back to its zero position, showing that the current has subsided. Now, however long the magnet NS is left stationary within the coil C, no current is produced. But if the magnet is quickly withdrawn, the galvanometer registers a current in the direction opposite to the current obtained by the introduction of the magnet. This current is also transient, and subsides when the magnet NS becomes stationary. If the south pole of the magnet is now introduced into the coil, the galvanometer shows a transient current opposite to that produced by the introduction of the north pole. The withdrawal of the south pole gives a transient current opposite to that caused by

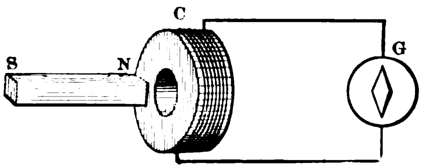

Fig. 10. Apparatus for showing the production of a transient electric current by the motion of a permanent magnet.

its own introduction, and in the same direction as that given by the introduction of the north pole.

Another way of obtaining a similar result is to employ two coils of wire placed near each other but not electrically connected, as shown in Fig. 11. One of these coils, S, which we will call the *secondary*, is connected with the galvanometer G, while the other, called the *primary*, P, may be connected with the terminals of a galvanic battery B. No current is shown in the galvanometer when a *constant* current is sent through the primary; but when the current in the primary is made, broken or reversed, transient currents are obtained in the galvanometer. That is to say, the current in the primary sets up a magnetic field linking with the secondary circuit. While the primary current is steady, this field is steady and no effect is obtained in the secondary. But variations of the current in the primary cause variations of the magnetic field and consequently currents in the secondary.

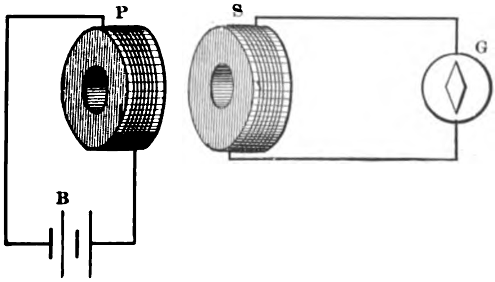

FIG. 11. Apparatus for showing electromagnetic induction.

The variable currents in the secondary are said to be *induced* by the variable currents in the primary, and the phenomenon is referred to as *electromagnetic induction*. It is in part by action of this kind that currents at the receiving station of a wireless telegraph system are produced by the action of variable currents at the sending station. The extension of the effects of electromagnetic induction to the case of two circuits widely separated from each other we shall see to be the result of the use of extremely rapid electric oscillations at the sending station.

On Mutual Induction. — Let us examine a little more specifically the case of electromagnetic induction described in the galvanometer experiment cited above.

This experiment shows that when the current in the primary coil is increasing, the current induced in the secondary coil is in the opposite direction to the primary current; while, if the current in the primary is decreasing, the current in the secondary is in the same direction as the primary current. Perhaps it would be better to speak of the *electromotive force*[1] in the secondary rather than the *current*, because the electromotive force in the secondary bears a simple relation to the current in the primary. The simple relation is, that the electromotive force in the secondary is proportional to the time rate of change of the current in the primary. If E_2 is the electromotive force induced in the secondary, I_1 the current in the primary, $\dot{I}_1$ the time rate of increase of the current I_1, then theory and experiment show that

$$E_2 = -M\dot{I}_1, \tag{1}$$

in which M is a constant depending on the form and position of the two circuits.

M is called the *coefficient of mutual induction*, or, more briefly, the *mutual inductance* of the two circuits. M is found to have the same value if the variable current is sent through the secondary and the electromotive force examined in the primary.

Consistent with the above equation, *the Mutual Inductance of two circuits is defined as the electromotive force induced in one of the circuits when the current in the other is changing at the rate of one unit current per second.*

The mutual inductance between two circuits is *increased* by *increasing* the number of turns on either or both of the circuits or by bringing the circuits nearer together, or by introducing iron or other magnetizable metals within the circuits. Methods of calculating the mutual inductance of circuits of various forms are given in Appendix II.

By a reference to equation (1) given above it is seen that the electromotive force induced in the secondary is increased by increasing the rate of change of current in the primary. That is, in order to get a large induced electromotive force at our receiving station we should have as large a current as possible at our sending station and change it as rapidly as possible. This result is best attained by the use of currents of high frequency at the sending station, such as are obtained by the discharge of a Leyden jar.

Self-Induction. — In the case of the two coils placed near together in the preceding discussion, it was found that the elec-

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[1] This term is defined in Appendix I.

tromotive force in the secondary is produced by a variable magnetic field from the primary interlinking with the secondary. Now, if instead of two coils we have one coil alone carrying a variable current, the variable current produces a variable magnetic field linking with the circuit itself, and in consequence a back electromotive force is produced in this coil tending to oppose the variation of the current in it. This action of the current on itself is called *self-induction.* The back electromotive force due to self-induction in the circuit is connected with the current in the circuit by the formula

$$E_1 = -L_1 \dot{I}_1, \tag{2}$$

in which L_1 is called the *coefficient of self-induction,* or, more briefly, the *self-inductance* of the circuit. $\dot{I}_1$ is an abbreviation for the time rate of change of the current. The subscripts 1 show that all the quantities refer to the same circuit.

Consistent with equation (2), *the self-inductance of a circuit may be defined as the back electromotive force of induction in the circuit when the current in the circuit is changing at the rate of one unit current per second.*

The numerical value of the self-inductance depends on the geometrical form of the circuit. In Appendix II formulas are given for calculating the self-inductance of some simple forms of circuit.

This discussion of self-inductance is here introduced in quantitative terms, because this quantity is of fundamental importance in the study of oscillatory currents. I am aware that the semi-mathematical form in which the idea is presented may fail to give a clear conception of the phenomenon, so I propose to attempt in the next chapter to describe self-induction by the aid of certain familiar analogies.

CHAPTER IV

ON THE RESEMBLANCE OF SELF-INDUCTION TO MECHANICAL INERTIA

In the previous chapter it has been pointed out that self-induction is the action of a variable current on itself due to the production of a variable magnetic field by the current. When a current of electricity flows in a circuit of any form, a field of magnetic force is set up and links with the circuit. The manner in which the flow of current in the wire produces magnetic effects in the surrounding medium is not completely understood, but that such effects exist is made evident by bringing a magnetic compass needle up near the circuit; the compass needle tends to set itself in certain intangible lines called *lines of magnetic force*. The lines of magnetic force produced by a current are closed curves linking with the wire carrying the current, as is shown by the compass needle or by the distribution of the iron filings depicted in Figs. 7, 8 and 9.

Experiments similar to those cited in the previous chapter show that when a change is made in the electric current in the wire, the magnetic field surrounding the wire is changed, and that these changes in the magnetic field impress back upon the circuit an electromotive force opposing the change of current. *The self-induction of an electric circuit may thus be described as a property that tends to prevent a change of the electric current in the circuit.*

In this respect self-induction resembles the property of inertia in matter. The inertia of a body is that property by virtue of which a body tends to persist in its state of rest or motion. If a body is at rest or is moving with a given velocity, the inertia of the body opposes a change of its state of rest or motion. In a similar manner, the self-induction in an electric circuit opposes a change of the electric current in the circuit.

From this it need not be inferred that electricity itself is a form of matter possessing inertia, because in the case of the electric current we may believe that *the inertia resides primarily not in the electricity but in the magnetic field set up by the current.*

The correctness of this belief is evidenced by the fact that with a fixed current flowing in a wire the self-induction may be greatly increased by bending the wire into the form of a coil. Now making the wire into a coil does not change the amount of electricity flowing in the wire, but it does change the strength of the magnetic field about the wire. The inertia of the current, therefore, has its existence not primarily in the conductor but in the medium surrounding the conductor.

The Contrast of Self-Induction with Resistance and its Resemblance to Inertia. — The self-induction of a circuit acts upon the current in a manner entirely different from the manner in which resistance acts. The resistance of a circuit always opposed the flow of the current, and when a current is sent through a conductor, some of the energy of the current is used up in overcoming the resistance of the conductor; or, more properly speaking, some of the electric energy is converted into heat. This is true whether the current is increasing or diminishing or is steady; and the heat developed is not again completely available for producing electric current, so that a continuous supply of energy is needed at the source of the electric current to keep up the current against the resistance of the circuit.

Self-induction, on the other hand, does not change the electrical energy into heat. When the current is steady, self-induction has no effect. If, however, the current is increasing, some of the energy supplied to the system is employed in establishing the magnetic field. If now the current is allowed to decrease by an equal amount, the energy stored up in the magnetic field is restored to the conductor and helps to maintain the current. Thus, during a cyclic[1] change of the current as much energy may be obtained from the magnetic field as was given to it.

Hence, if we have an oscillatory current in a circuit, none of the energy of the current is consumed by the action of the self-induction, and the supply of energy at the source is wasted only in overcoming the resistance of the circuit.[2]

It is apparent that in respect to the consumption of energy self-induction resembles inertia in matter. Energy is required in order

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[1] A cyclic change is a change from any value A to any other value B, and from B back to A again.

[2] Later we shall see that for some forms of circuit this statement is not strictly true, because some of the energy may be radiated as electric waves. Also in the case of some media, as *iron*, in the field of magnetic force, some of the energy is converted into heat by *hysteresis*.

to set a heavy body in motion, but this energy is recovered when the body is stopped, and the only loss of availability of energy in a cyclic process in which a body is started in motion and stopped again is that lost in overcoming friction in the machinery used for starting and stopping the body.

When a body is set in motion, the energy supplied in producing the motion is stored up in the body as kinetic energy, so that analogously many writers refer to the energy of the magnetic field as kinetic in character. Without necessarily committing ourselves to this specific proposition as to the kinetic character of the magnetic field, it will still be useful to keep in mind that self-inductance opposes changes in the electric current in the same general manner as inertia opposes changes in the motion of bodies.

Keeping this analogy in mind, we can easily foresee many of the facts about the flow of electricity; for example, suppose that a rapidly alternating electromotive force is applied to a circuit containing a large self-inductance; usually only a small current will flow, just as only a small motion will generally be communicated to a heavy body by a rapidly varying material force. There are, however, special cases in which the periodic force will set up a large motion of the material body. This happens when the period of the force is the same as the natural period of the body. But in order for the body to have a natural period something besides inertia is required; namely, the body must be elastic or must be elastically attached to something. So in the case of the electric circuit it is also possible to get a large current with a rapidly varying electromotive force, provided the circuit contains besides its self-inductance a suitable amount of *electrostatic capacity,* which will be shown to supply the factor required to give periodicity to the electric circuit.

Before developing further our notions in regard to self-inductance, it is proposed to introduce this other phenomenon that enters prominently into the discussion of electric waves; namely, the phenomenon of electrostatic capacity.

CHAPTER V

ON ELECTROSTATIC CAPACITY

THE last two chapters have been devoted to a discussion of electric currents and the magnetic field accompanying such currents. In order to arrive at a conception of the nature of electric waves it is necessary also to give some attention to the action of electric charges at rest. This is the subject of *electrostatics*. Here again we must look to Faraday for the fundamental discoveries. In the beginning paragraph of his most important research on this subject Faraday says:[1]

"To those philosophers who pursue the inquiry zealously yet cautiously, combining experiment with analogy, suspicious of their preconceived notions, paying more respect to fact than to theory, not too hasty to generalize, and above all things, willing at every step to cross-examine their own opinions, both by reasoning and by experiment, no branch of knowledge can afford so fine and ready a field for discovery as this."

Influence of Intervening Medium on Electric Attraction. — The result obtained by Faraday in the research referred to is that the electrostatic repulsion or attraction between two charged bodies is influenced by the medium intervening between the charged bodies. If, for example, we have two flat metallic plates placed parallel to each other, and we charge one of the plates positively and the other negatively, the electrostatic attraction between the two charges on the plates will be less when the plates are separated by glass than when they are separated by air, provided the plates are charged with the same quantity of electricity in the two cases. The attraction between the charges on the plates with glass intervening will be about one-sixth as much as that with the same thickness of air intervening; so that in order to get the same force between the charges on the plates in the two cases we must put upon the plates with glass between them six times as much electricity as is required with air between.

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[1] Faraday: Experimental Researches in Electricity and Magnetism, Vol. I, Eleventh Series, Nov., 1837.

We thus come to the result that the insulating medium between the oppositely charged metallic plates serves not merely to separate the plates and prevent them from losing their charge, but serves also to determine the charge the plates will receive for a given electromotive force; for example, a given battery connected between the plates. And since the insulating medium between the plates has other functions than merely to insulate, Faraday proposes to designate the insulating medium by the name *dielectric*, when reference is made to the force acting through it. He says, " I use the word *dielectric* to express that substance through or across which the forces are acting."

On Condensers. — The apparatus consisting of two conducting bodies separated by a dielectric is called a *condenser*. An ordinary Leyden jar, consisting of two metallic coatings separated by glass, is a familiar case of an electric condenser. Any two conducting bodies with a dielectric between constitute a condenser. As an extreme case, a single conducting body isolated in space is considered a condenser, with empty space as dielectric, and with the other conductor removed to an infinite distance. As another example, a charged body in the neighborhood of the earth is a condenser, with the earth for the other conductor and with air as dielectric.

Capacity of Condenser. — Different condensers are said to have different capacities, which term does not refer to the total amount of electricity that the condensers can contain, but to the quantity of electricity they will take under the action of a given electromotive force; namely, a unit electromotive force. In the practical system of units (see Appendix I), the unit of electromotive force is the *volt*, the unit of quantity of electricity is the *coulomb*, and the unit of capacity the *farad*. A farad is the capacity of a condenser that can be given a charge of one coulomb under the action of electromotive force of one volt. The farad is a very large unit of capacity; for example, the electrostatic capacity of the whole earth is only about .000708 farad. That is to say, it would take only about seven ten-thousandths of a coulomb to raise the potential of the earth one volt. Since the farad as a unit is very large, the capacity of a condenser is often designated in millionths of a farad, or *microfarads*.

The quantity of electricity, Q, on each plate of a condenser of capacity C is $Q = CV$, where V is the difference of potential between the plates.

Dielectric Constant. — Returning, now, to the function of the dielectric in determining the capacity of a condenser, the term *dielectric constant* of a substance is used to designate the capacity of a condenser with the substance as dielectric relative to the capacity of the same condenser with empty space as dielectric. The dielectric constant of air and all the gases at ordinary pressure is approximately unity; this means that the capacity of a condenser with a gas as dielectric is not much changed when the gas is pumped away. In the example cited above the dielectric constant of a particular glass is given as six; that is, the quantity of electricity that a condenser will contain under a given electromotive force with this glass as dielectric is six times the quantity the condenser will contain under the same electromotive force when air is substituted for the glass. A table of dielectric constants, together with some numerical formulas for calculating the capacity of some simple forms of condenser and rules for combinations of condensers in series and parallel, is given in Appendix II.

General Facts about Energy and Electromotive Force of Charged Condenser. — In order to send a charge of electricity into a condenser, energy is required, but the energy is not converted into heat, as it is in the case of a current of electricity flowing through a resistance; for the energy of the charge may be recovered as electric energy when the condenser is allowed to discharge. In a cyclic process in which a condenser is charged and discharged again, there is no loss of availability of energy in the processes that occur in the condenser. And when a condenser charges and discharges several times in an oscillatory manner, it is necessary to supply energy from without only in so far as the electric energy is radiated or is converted into heat in flowing through some resistance in the circuit.[1]

It has undoubtedly been observed by the reader that in respect to the reception of energy from the circuit and the return of the same amount of energy to the circuit again the medium of the condenser behaves somewhat like the medium of the magnetic field. There is, however, one marked difference. In the case of the magnetic field, the opposing *electromotive force* called into play by self-induction *is proportional to the rate at which the current is changing;* while, in the case of the condenser, the *electromotive force* V opposing the flow of electricity into the condenser *is proportional*

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[1] This statement is not always strictly true, because in some forms of condenser a small part of the energy is consumed by *hysteresis* in the dielectric.

to the quantity Q of electricity in the condenser. Numerically $V \sim Q$, and in proper units $V = \frac{Q}{C}$, where C is the capacity of the condenser.

Mechanical Systems Analogous to an Electrical Condenser. — I. We have a condition of things analogous to the charging of a condenser in the act of supplying water to a tall cylindrical reservoir. The force P required to send water into the reservoir against the hydrostatic pressure of the water already in the reservoir is proportional to the height h of water in the reservoir, which is proportional to the amount of water M in the reservoir. Numerically, in suitable units $P = \frac{M}{S}$, where S is the area of cross section of the reservoir. S may be looked upon as analogous to C.

II. Another analogue to the action of a condenser is found in the forces called into play in the act of compressing an elastic spring. The restoring force F of the spring is proportional to the amount x by which the spring is compressed. Numerically, $F = ex$, where e is the stiffness of the spring.

In the case of the condenser it should be borne in mind that the greater the capacity of the condenser the less the electromotive force required in order to charge it with a given amount of electricity. In this respect capacity of the condenser resembles the reciprocal of the stiffness of the spring, for the greater the stiffness e of the spring the greater the force F required to compress it by a given amount.

Flow of Current in a Circuit Containing a Condenser. — The reader will note the following fundamental facts in regard to the action of a condenser. If a battery having a constant electromotive force E has its positive pole connected to one plate of a condenser and its negative pole connected to the other plate, electricity will flow into the condenser and charge it. As the condenser charges it gives rise to a back electromotive force opposing the flow, so that the current is diminished more and more by the opposing e.m.f. of the condenser, as the condenser is charging. The e.m.f. at each instant is proportional to the quantity q of electricity in the condenser and is inversely proportional to the capacity C of the condenser. When this opposing e.m.f. becomes equal to the e.m.f. of the battery, E, the flow of electricity ceases. Then $E = \frac{Q}{C}$ where Q is the final charge attained by the condenser. After this condition is reached, no further current flows. This process of charging the condenser is described as gradual because time is required for the final condition to be established, but this time is usually very short.

Work Done in Charging Condenser. — During this process of charging the condenser, the average e.m.f. of the condenser was $\frac{1}{2} E$; the work[1] done, which is the charge introduced multiplied by the e.m.f. of the condenser, is $Q \times \frac{1}{2} E$; or, substituting for Q its value EC, the work W done in charging the condenser is

$$W = \tfrac{1}{2} E^2C.$$

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[1] See definitions of electrical work, in Appendix I.

CHAPTER VI

ON THE DISCHARGE OF A CONDENSER THROUGH AN INDUCTANCE AND RESISTANCE

The Oscillatory Discharge. — We are now ready to undertake a more critical examination of the proposition set down in the first chapter that, under certain conditions, the discharge of a Leyden jar is oscillatory. As a mechanical analogy, let us consider the motion of a heavy bob attached to an elastic spring. Let the position of rest of the bob be the position *a*, Fig. 12. If now the bob is pulled down to a position *b* and released, the spring draws it back again to *a*. During this process the bob acquires a velocity determined by the stiffness of the spring and the mass of the bob. When the bob reaches *a*, the spring ceases to pull, but the bob by reason of its inertia moves on up to a position *c*, during which process the spring is compressed. When the bob has reached *c*, it has lost its velocity and is now driven back by the compressed spring. In this way the vibratory motion is kept up for some time, and would be kept up indefinitely but for the fact that the resistance of the air and the imperfect elasticity of the spring convert some of the energy into heat during each excursion, so that the amplitude of the motion is diminished more and more until the body finally comes to rest at *a*.

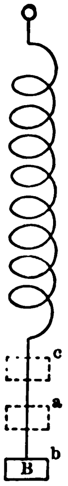

Fig. 12. Spring and bob for illustrating oscillatory motion.

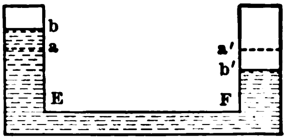

Fig. 13. Water column showing vibratory motion.

As another illustration, suppose a body of water to be contained in a bent tube of the form of Fig. 13. Let the surface of the water in its position of rest be at *a* and *a'* in the two arms of the tube. Suppose now that the water is moved into the position *bb'* and released. The column of water will vibrate back and forth in the tube so that its level in the left-hand arm of the tube comes successively above and below the position *a*. During each excursion the amplitude of the motion is diminished till the water finally comes to rest in its initial position.

Both of these forms of mechanical vibratory motion are easily realized in practice, and both bear a marked resemblance to the flow of electricity in the discharge of a condenser through an inductance and resistance.

In order now to understand how a condenser discharge may be oscillatory in character, suppose a Leyden jar, or other form of electrical condenser, of capacity C to be initially charged, say from an electric machine, with a quantity of electricity $+Q_0$ on one plate and $-Q_0$ on the other. And suppose that the condenser has in series with it a self-inductance L, and a spark gap S. (Fig. 14.) At first let the spark gap be too wide for the spark to pass. Positive electricity will be distributed over the one coating and one knob of the spark gap, and negative electricity will be distributed over the other coating, the coil L and the other knob of the spark gap.

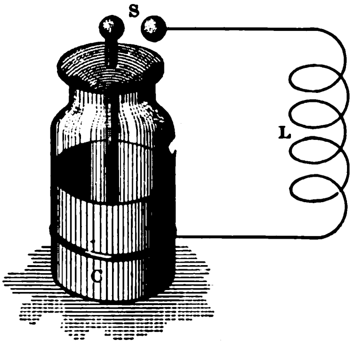

FIG. 14. Leyden jar, inductance coil, and spark gap.

Let V_0 be the difference of potential between the plates of the condenser. Before the current starts there will be the same difference of potential between the knobs of the spark gap, because all parts of a conductor in which no current is flowing are at the same potential.

Let us suppose, now, that the knobs of the spark gap are made to approach each other until the gap is short enough for the potential to start a spark (i.e., about 39,000 volts to the centimeter, if the terminals of the gap are balls 1 cm. in diameter). When the spark starts, the resistance of the gap suddenly drops to a very small value, in some cases to a small fraction of an ohm,[1] and the electric current begins to flow across the gap under the action of the high difference of potential between the plates.

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[1] We have seen in Chapter II that a spark is one of those agencies that render gases conductive.

The current flowing through the circuit has a small value when the spark first begins to pass. If it were not for the self-induction of the circuit, the current would spring to a large value, because the electromotive force of the circuit is high and its resistance low. We have seen, however, that the self-induction acts in such a manner as to oppose rapid changes in the current. As a result the current requires time to attain its maximum. When the current reaches its maximum, the condenser is completely discharged, but there is a large current flowing. This current cannot stop at once, for the self-induction now acts in the reverse direction and opposes the decrease of the current, so that the current continues to flow after the electromotive force of the condenser has become zero. This process charges the condenser oppositely to its original charge, and when the current in this direction ceases, the back electromotive force of the condenser starts the current in the reverse direction. The condenser is again charged in its original direction, the current again reverses and the process continues for a number of oscillations depending on the resistance, self-inductance and capacity of the circuit.

The essential factors entering into the production of the oscillatory discharge are the self-inductance and the capacity of the circuit, characterized in their actions by the fact that they are out of phase with each other, so that when the effect of the capacity is a maximum that of the induction is a minimum, and *vice versa.*

On account of the resistance of the circuit some of the electrical energy is converted into heat during each flow of the current, so that the maximum attained by the current at each oscillation falls lower and lower until the spark ceases. The decrease of the amplitude of the oscillation under the action of the resistance is referred to as *damping* of the oscillation by the resistance. It will be seen later that the radiation of energy as electric waves acts also in a manner to damp the oscillations.

Criterion. — In his mathematical investigation of this problem Sir William Thomson showed that the discharge occurs in the oscillatory manner here described only when the resistance of the circuit does not exceed a certain value relative to the ratio of the self-inductance to the capacity of the circuit. The exact expression of this condition under which the discharge is oscillatory is,

$$R^2 < 4\,L/C.$$

Non-oscillatory Discharge. — If, on the other hand, R^2 is greater than $4\ L/C$, Thomson showed that the discharge is unidirectional; that is, no reversal of the sign of the charge takes place. We should have an analogous condition of affairs with the elastic spring used as an illustration if the bob B (Fig. 12) should be submerged in a liquid, provided the liquid should offer sufficient resistance to the passage of the bob through it. Evidently the amount of resistance required to prevent the oscillation of the bob will increase with increase of the inertia of the bob and with increase of the stiffness of the spring. The former of these corresponds to L, and the latter to the reciprocal of C, so that the fact that L/C will occur in the condition for the oscillation or non-oscillation of the electrical system might have been anticipated.

In the case of the water column, if the connecting tube EF between the two vertical cylinders in Fig. 13 is made sufficiently small to offer enough friction, the motion of the water will also be non-oscillatory. This is analogous to the case of the non-oscillatory discharge of the condenser.

Mathematical Formulas for the Discharge of the Condenser.— Thomson derived the following equations for the current i at any time t, where t is measured in seconds from the time when the discharge begins:

Case I. If $R^2 < 4\ L/C$,

$$i = \frac{2V_0}{\sqrt{\frac{4L}{C} - R^2}}\, e^{\frac{-Rt}{2L}} \sin\left\{\frac{\sqrt{4\ LC - R^2C^2}}{2\ LC}\, t\right\}, \tag{3}$$

in which $V_0 =$ the initial difference of potential,
$R =$ the resistance,
$L =$ the self-inductance,
$C =$ the capacity, and
$e = 2.718281\ldots$ (base of natural logarithms).

This is the case of the oscillatory discharge.

Case II. If $R^2 > 4\ L/C$,

$$i = \frac{V_0}{\sqrt{R^2 - \frac{4L}{C}}} \left\{e^{-\frac{t}{T_2}} - e^{-\frac{t}{T_1}}\right\}, \tag{4}$$

in which $T_1 = \dfrac{2\,LC}{RC - \sqrt{R^2C^2 - 4\,LC}}$, and

$$T_2 = \frac{2\,LC}{RC + \sqrt{R^2C^2 - 4\,LC}}$$

This is the general case of non-oscillatory discharge.

Case III. If $R^2 = 4\,L/C$,

$$i = \frac{V_0 t}{L} e^{\frac{-Rt}{2L}} \tag{5}$$

This is the critical case, in which the discharge is just non-oscillatory.

Graphical Representation of Results. — By the aid of the equations (3), (4) and (5) the current in the condenser circuit at any time can be calculated in any case in which the constants of the circuit and the initial difference of potential of the plates of the condenser are known; of the calculated values so obtained we can construct a table, in the first column of which we may place the time in convenient fractions of a second, and in the second column we may write the different values of the current corresponding to these different values of the time.

There is, however, another method of representing the results, which affords an easier comprehension. This is the *graphical method,* and consists in constructing a curve on a sheet of squared paper with a scale of time and a scale of current at right angles to each other. As an example of this method of showing results, let us refer to Fig. 15, which is a graphical representation of the flow of current in a condenser circuit in which the resistance is supposed to be zero. The horizontal scale through the center of the figure gives the time in millionths of a second; the vertical scale at the left of the figure gives the current. Such a diagram gives the current at any time; for example, when the time is zero, the current is zero. To get the current at one one-millionth of a second, one goes out on the horizontal line to one one-millionth second (which is halfway between 0 and 2), and at this point one erects a vertical line which will be seen to cut the curve at a point the same height as 150 amperes on the margin. This 150 amperes is, then, the current at $\frac{1}{1000000}$ sec. In like manner, at $\frac{3}{1000000}$ sec., the current is seen to be about minus 130 amperes.

From this description of the method of interpreting the curves it will be evident how the curves are drawn; namely, a table is made of current for different values of time, by the aid of formula (3), and then for each value of time plotted horizontally the corresponding value of current is erected vertically, and through the points so obtained a smooth curve is drawn. This process resembles the method employed by navigators to show the route of a ship. Each day, or oftener, an observation of latitude and longitude is made, and a point is put on the map at the intersection of the given latitude and longitude; and through the points thus obtained at successive observations a smooth curve is drawn, which represents the course of the ship, and from which the position of the ship at points intermediate between the observations may also be approximately obtained.

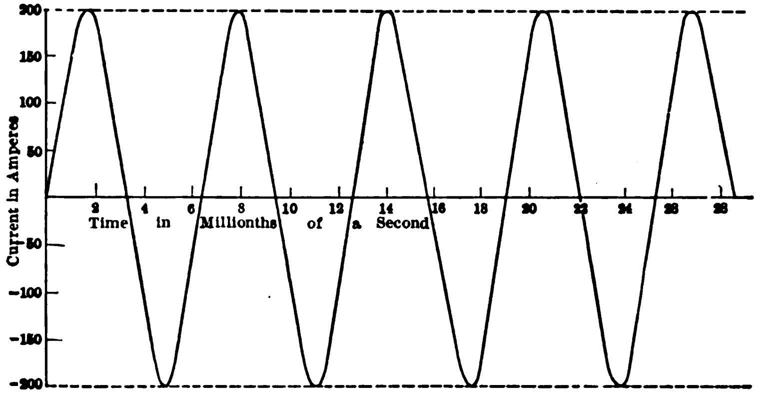

FIG. 15. Current from a condenser of capacity .01 microfarad discharging through an inductance of .0001 henry. Initial potential 20,000 volts. Resistance zero.

Curves Showing Condenser Discharge. — The manner in which the discharge of a condenser occurs under different conditions is represented graphically in the curves of Figs. 15, 16, 17 and 18. In these curves the time in millionths of a second is plotted horizontally, and the current in amperes is plotted vertically. These curves are calculated from the formulas given on page 31. In all four cases the capacity, self-inductance and initial potential are the same; namely, $C = 10^{-8}$ farads, $L = 10^{-4}$ henrys, $V_0 = 20{,}000$ volts. The only difference between the conditions of the discharge in the four cases is the difference in resistance of the circuit through which the discharge occurs.

In Fig. 15 the resistance is supposed to be zero, and we have as a result what is called an undamped oscillation. The current oscillates back and forth between a positive maximum of 200 amperes and a negative maximum of 200 amperes.

In Fig. 16 the resistance of the circuit is 10 ohms, and in Fig. 17 this resistance is 20 ohms. These two curves show how the current is damped by the resistance of the circuit. The curves of Figs. 15, 16 and 17 all come under the conditions of Case I.

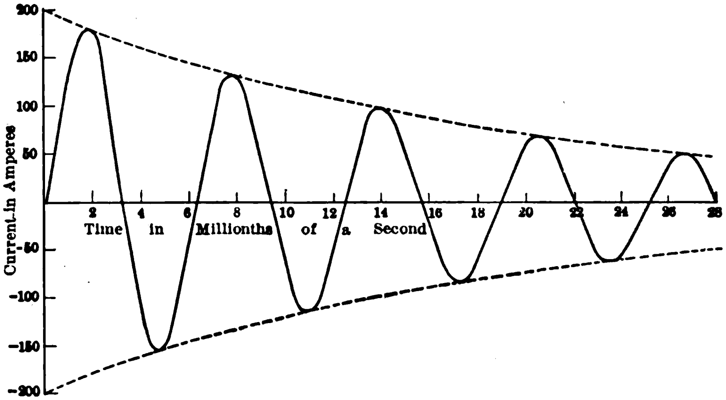

FIG. 16. Same as Fig. 15, except that the resistance is 10 ohms.

If, however, the resistance be 200 ohms, we have the condition for the current to be just non-oscillatory, $R^2 = 4\,L/C$, and the equation of the curve is then the equation given under Case III. This kind of discharge is shown in the curve of Fig. 18. This

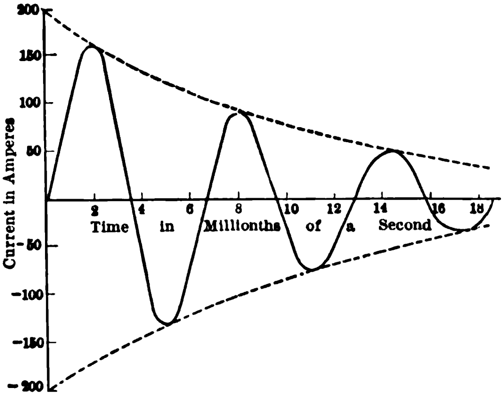

FIG. 17. Same as Fig. 15, except that the resistance is 20 ohms.

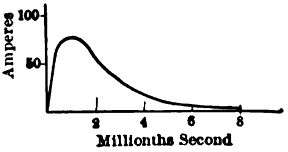

FIG. 18. Same as Fig. 15, except that the resistance is 200 ohms.

case has also the same capacity, self-inductance and initial voltage as the preceding cases, but the current is seen to rise only to about 75 amperes and then gradually to approach zero.

If the resistance be made greater than 200 ohms, we have Case II, in which the discharge is also non-oscillatory. A curve representing this case is not given; the form of such a curve is somewhat like that of Fig. 18, with the exception that the curve does not rise to so great a value and does not approach zero so rapidly as does the curve in Fig. 18.

The Period of Oscillation. — From equation (3), p. 31, it can be shown that the period of a complete oscillation of the current, in case the discharge is oscillatory, is

$$T = 2\pi \frac{2\,LC}{\sqrt{4\,LC - R^2C^2}}, \tag{6}$$

in which T is the time of a complete oscillation in seconds; L, C and R are measured in the same set of units; e.g., henrys, farads and ohms respectively; π is 3.1416 . . . , the ratio of the circumference to the diameter of a circle.

Equation (6) is the exact expression for the period, but in most practical cases that occur in the use of electric waves it is found that the effect of the resistance is inappreciable in its effect on the period; that is, in equation (6), R^2C^2 is small in comparison with $4\,LC$, so that the expression for the time of a complete oscillation simplifies to

$$T = 2\pi\sqrt{LC}. \tag{7}$$

This formula is usually sufficiently accurate. For example, in the case plotted in Fig. 16, the period of oscillation calculated by equation (7) differs from the exact value, obtained from equation (6), by one-fourth of one per cent

The various formulas given in this chapter were first obtained mathematically by Sir William Thomson in 1855. In 1859 Feddersen demonstrated the oscillatory character of the discharge by a revolving mirror photograph of the spark, similar to the photograph shown in Fig. 3 of Chapter I. Since then all of Thomson's equations have been submitted to careful tests and have been found to be accurate.

CHAPTER VII

MAXWELL'S THEORY. ELECTRIC WAVES. THE ELECTROMAGNETIC THEORY OF LIGHT

In the preceding chapter we have seen that when a condenser, in series with a self-inductance and resistance, is charged and allowed to discharge, the current obtained, if the resistance is not too large, will be oscillatory in character. In this arrangement of apparatus we have a mechanism that serves as the source of electric waves.

In 1865 Maxwell predicted, by mathematical reasoning based on some experiments of Faraday, that variable currents in a conductor produce electric waves in space, that these electric waves travel with the velocity of light, and that light itself consists of electric waves of extremely short wave lengths. While direct experimental verification of this theory — by the actual discovery of electric waves — did not come during Maxwell's lifetime, Maxwell yet showed that his predictions were strongly supported by many of the known facts about electricity and light.

Without the aid of mathematics it is difficult to follow the steps of Maxwell's reasoning, so that the discussion here given will undoubtedly appear to the reader to be inconclusive. In the next chapter we hope to remedy this defect of the theoretical discussion by a description of the actual experimental demonstration of the chief propositions of Maxwell's theory.

In the derivation of his theory Maxwell makes use of the two facts about the relation of electricity to magnetism that we have given in Chapter III; namely,

I. An electric current in a conductor produces a magnetic field in the neighborhood of the conductor, and

II. A variable magnetic field in the neighborhood of a conductor produces an electromotive force in the conductor.

To these two well-known experimental facts Maxwell adds a third proposition in the form of an assumption, which has been called the *displacement assumption.*

The Displacement Assumption. — This assumption is an attempt on the part of Maxwell to give expression to the idea of Faraday, that when a condenser is charged, the condition of things is not completely described by saying that a positive charge is given to one plate and a negative charge to the other plate of the condenser. Faraday showed that something takes place in the medium between the plates, and Maxwell makes the assumption that the action in the medium partakes somewhat of the nature of an electric current, although the medium is an insulating substance.

It is difficult to determine just how Maxwell imagined this action to take place, and different writers have employed different mechanisms in the description of the current that Maxwell supposed to exist in the insulators. One way of representing his idea is to suppose that the insulating medium, whether a solid, liquid, or gaseous dielectric, or even empty space, is made up of small parts, and to suppose that the electricity in these small parts of the insulator may flow freely in the small parts but cannot flow from one part to the next. If we call these small parts molecules, we may describe the current in the insulating medium as the act of polarizing the molecules. That is, for example, when the left-hand plate of the condenser in Fig. 19 is charged positively, the positive electricity added to this plate attracts the negative electricity and repels the positive electricity of the neighboring molecules, so that the part of each molecule near the plate becomes negative and the distant part becomes positive. Molecules in this condition are said to be polarized. The layer of molecules so polarized acts on the next layer and produces a similar polarization, so that in turn the molecules throughout the medium between the plates become polarized.

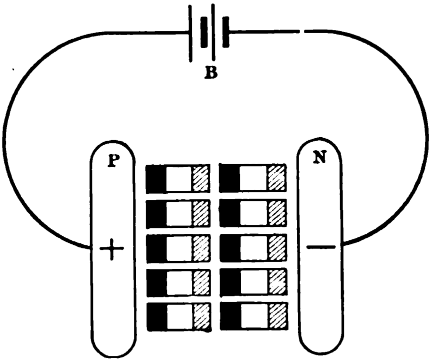

FIG. 19. Illustrating displacement current.

It is seen that this general transfer of positive electricity to the right and negative electricity to the left in the molecules would have an effect similar to an electric current flowing from the positive plate to the negative through the insulator. Maxwell called this general transfer of electricity in the dielectric a *displacement current*. During the charging of the condenser, the displacement current is in the same direction as the current in the conducting parts of the circuit, so that the displacement current may be said to complete the conduction current. During the discharge of the condenser the dielectric loses its polarity, and according to Maxwell's view, gives rise to a displacement current in the dielectric. In this case, also, the displacement current completes the conduction current, which is now flowing away from the positive plate of the condenser.

It has been stated above that the displacement current partakes of the nature of an electric current. The displacement current differs from the ordinary current in that there is within the molecules nothing corresponding to ordinary resistance, so that none of the energy of the displacement current is converted into heat. The displacement current also differs from the conduction current in that the displacement current, under a given applied electromotive force, sets up a restoring force in the dielectric which, like the reaction of a compressed spring, soon becomes large enough to equalize the electromotive force and stop the current; whereas the conduction current in a circuit that is wholly conductive continues to flow as long as the electromotive force is applied to the circuit.

These are the differences between the displacement current and the ordinary current. On the other hand, according to Maxwell's theory, the displacement current is exactly like an ordinary electric current in respect to its relation to the magnetic field. We may thus add to the two propositions stated on p. 36, the proposition

III. In the case of a circuit not entirely closed by conducting parts, the current in the conducting parts is completed by a displacement current through the dielectric. This displacement current produces a magnetic field in its neighborhood; and a variable magnetic field in a dielectric produces displacement currents in the dielectric.

Electric Waves. — In Maxwell's treatise the propositions I, II and III are discussed quantitatively, with the result that he obtains a number of quantitative relations about light and electricity. However, without such a mathematical discussion we may be able to see how the facts assumed to be correct in proposition III lead to the idea of electric waves in the dielectric.

For this purpose let us suppose that we have two conducting bodies of the form shown in Fig. 20. *A* and *B* are two metallic rods with a small spark gap between. Suppose now that *A* is charged with electricity of one sign, and *B* with electricity of the other sign, and suppose the charges are gradually increased until a spark passes between them. If the resistance is not too large, the current that flows will be oscillatory, because the rods have electrostatic capacity and self-inductance. The two metallic rods here pictured constitute an electric " oscillator."

According to Maxwell's theory, the oscillatory currents in the oscillator will be completed by displacement currents in surrounding space. A part of this displacement current takes place along the black loops in the direction of the arrows from one end of the oscillator around to the other. The displacement loops are really sections of a sheet such as would be obtained if we rotated the figure about the oscillator as an axis. These displacement currents in the sheet will reverse their direction when the current in the oscillator reverses, and are accompanied by a magnetic field of which a single line is shown encircling the displacement sheet. The magnetic field produced by the displacement current in the shaded region, being oscillatory in character, will induce displacement currents in a portion of the medium farther out from the oscillator, and the latter current will lag somewhat behind the former. Thus, a sheet corresponding to the shaded region will sustain a displacement current oscillating with the period of the oscillator. The unshaded region farther out will sustain similar oscillations a little later, so that we have the condition of things that exists in a wave motion traveling with a finite velocity; namely, a series of disturbances first in one direction, then in the opposite direction, taking place all over a closed surface, and traveling outward from the source.

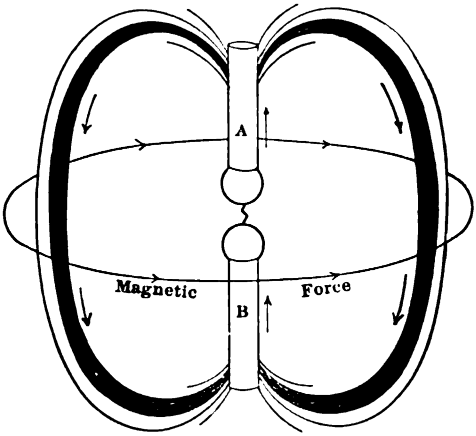

FIG. 20. Displacement current and magnetic force.

Properties of the Electric Waves. — A masterly mathematical treatment by Maxwell of this idea of an electric displacement in dielectric media led not only to great progress in the knowledge of electromagnetism, but also to a complete revision of theories as to the nature of light, so that now all the phenomena of optics are describable in terms of Maxwell's electric waves. From his theory Maxwell deduced the following facts in regard to electric waves:

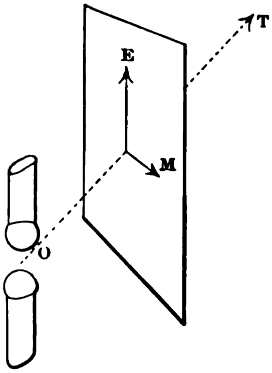

FIG. 21. Electric force E and magnetic force M perpendicular to direction of propagation T.

1. The electric wave in the dielectric consists of a displacement current in one direction with a magnetic force at right angles to it, both of these quantities being in the wave front; that is to say, at right angles to the direction of propagation of the wave (see Fig. 21). *Thus electric waves, like light waves, are transverse waves.*

2. The velocity of propagation of the electric waves (in a non-magnetic insulating medium) is $\frac{a}{\sqrt{k}}$, where a is the ratio of the c. g. s. electromagnetic unit of quantity to the c. g. s. electrostatic unit of quantity,[1] and k the dielectric constant of the medium. In empty space, by definition, k is unity, and the ratio a was known from older experiments to be the velocity of light (3×10^{10} cm. per second); whence *the velocity of the electric waves in free space is identical with the velocity of light, which is* 3×10^{10} *cm., or about* 186,000 *miles (seven times around the earth) in one second.*

3. In an insulating medium other than free space (for example, in glass or paraffin) it is seen from the preceding section that the velocity of the electric waves is

$$v = \frac{a}{\sqrt{k}} = \frac{v_0}{\sqrt{k}}, \tag{8}$$

in which v_0 is the velocity of waves in free space, and v the velocity of the waves in a dielectric of dielectric constant k; whence,

$$v_0/v = \sqrt{k} \tag{9}$$

That is to say, *the index of refraction*[2] *of a medium for electric waves is equal to the square root of the dielectric constant of the medium.*

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[1] For definitions of these units see Appendix I.

[2] The index of refraction is the ratio v_0/v.

4. All good conductors are opaque to electric waves, all good insulators are transparent to electric waves, and semiconductors like wood and stone are semitransparent. Metallic surfaces are practically perfect reflectors of electric waves.

The Electromagnetic Theory of Light. — Among these several properties of electric waves the properties stated in 1 and 2 are identically true of electric waves and light; while the properties enumerated in 3 and 4 have also met with very useful application to light as well as to longer electric waves. Thus Maxwell came to the conclusion that light waves are electric waves of short wave length. This theory is now generally accepted.

It is interesting to note, on this theory, how light can be produced. We have seen how electric waves may be produced by oscillating electric currents in a circuit of the form shown in Fig. 20. Now if we suppose the oscillator of Fig. 20 to be made smaller and smaller, the capacity and inductance will both be decreased, and the time of oscillation is thereby decreased. If then we think of the oscillator as possessing atomic dimensions, the period of oscillation approaches that of light. It is, however, not necessary to think of an actual electric discharge taking place between the atoms of our atomic oscillator, because the rapid vibratory motion of a single charged particle, or electron, back and forth would have the same effect as an electric discharge between particles, and would produce electric waves of which the period, for a particular size and velocity of the vibrating particle, would be the period of light of some particular color.

Let us turn next to the experimental demonstration of the existence of the electrical waves predicted by Maxwell. This did not come during Maxwell's lifetime; in fact, twenty-two years elapsed between Maxwell's remarkably clear presentation of the theory and Hertz's brilliant confirmation of it.

CHAPTER VIII

THE EXPERIMENTS OF HERTZ

THE first direct experimental confirmation of Maxwell's theory of electric waves was made by Professor Heinrich Hertz [1] of Karlsruhe in 1888. At Karlsruhe, and later at Bonn, Hertz performed a great number of experiments, in which he produced and detected electric waves; measured the wave length; showed that the electric waves were transverse, polarized waves; that they were capable of reflection from metallic surfaces and were freely transmitted through insulators; that they could be refracted by prisms of pitch and other dielectrics; and that as the wave length of the electric waves was shortened, the electric waves showed properties more and more analogous to the properties of light.

Lodge's Resonance Experiment. — Prior to the work of Hertz, Sir Oliver Lodge [2] in England had made some experiments on the inductive action between Leyden-jar circuits which were a close approach to the discovery of electric waves. A description of these experiments will aid us to understand Hertz's apparatus. Lodge employed two circuits of the form shown in Fig. 22. The Leyden jar A had its two coatings connected with an electric machine, so that when the machine was operated, the jar was charged, and when the tension of the charge reached a certain value, a discharge occurred through the loop BCD and across the spark gap S. This discharge was oscillatory and acted inductively upon a second circuit $A'B'C'D'$ placed parallel to the first. The second circuit was provided also with a spark gap at S', which was formed by a strip of metal folded over the jar so as to touch the inner coating and come near the outer coating as S'. This circuit, which we shall call the receiving circuit, had its period of oscillation variable in that the inductance of the circuit could be changed by the movable slider at $C'D'$. When sparks were passing in the discharge circuit, Lodge found that there was a certain position of the slider $C'D'$ that gave a maximum effect at the receiving circuit, as was shown by the lively passage of sparks

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[1] Electric Waves, translated by D. E. Jones, Macmillan & Co., 1893.

[2] Lodge: Report British Association, Vol. 50, p. 567, 1888.

across the spark gap at S'. The two circuits were then in resonance; that is to say, they had the same period of oscillation as determined

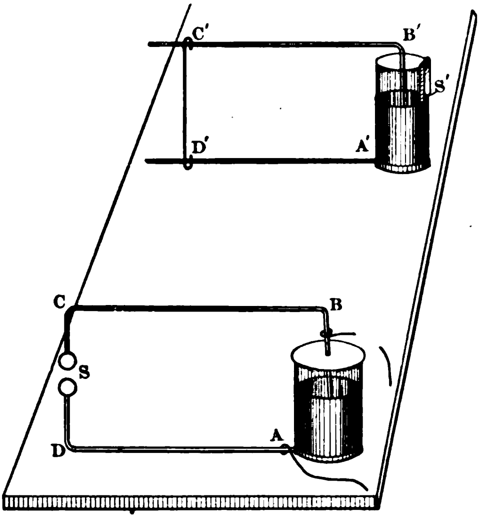

FIG. 22. Sir Oliver Lodge's resonant Leyden jars.

by the formula $T = 2\pi\sqrt{LC}$. The oscillatory current in the discharge circuit induced an electromotive force in the receiving circuit, and when the circuits were in resonance, this induced electromotive force was capable of forcing sparks across the gap at S', even when the two circuits were several meters apart.

According to Maxwell's theory, the inductive action between the two circuits consisted of electric waves sent out from the discharge circuit and striking the receiving circuit; but Lodge was not able to demonstrate the existence of these waves. To do this it was necessary to make the wave length shorter and the radiation freer than that produced by Lodge's discharge circuit.

Hertz's Experiments with Electric Waves in Air. — In order to produce shorter waves than those employed by Lodge, Hertz made use of a discharge system with smaller capacity and self-inductance. One form of Hertz's "oscillator" is shown in Fig. 23. It consists of two flat metallic plates, 40 cm. square, each attached to a rod 30 cm. long. The two rods were placed in the same line, and were provided at their nearer ends with balls separated by a spark gap about 7 mm. long. The oscillator was charged from the secondary of a Ruhmkorff coil J attached to the rods near the spark gap. The primary of the coil was fed by a battery, and contained a vibrator for interrupting the primary current so as to produce a high potential in the secondary. At each interruption by the vibrator in the primary, the two halves of the oscillator became charged, and discharged in an oscillatory manner across the spark gap of the oscillator. At each spark, according to Maxwell's theory, there was sent out a train of waves from the oscillator.

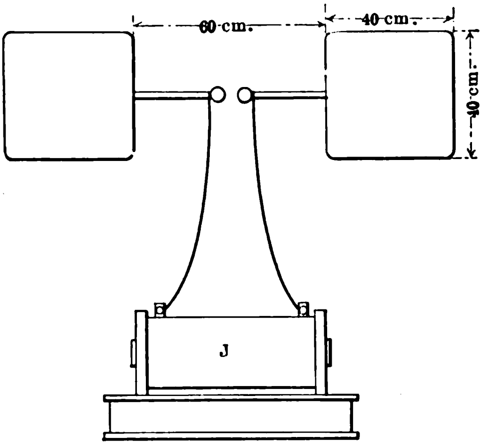

FIG. 23. Hertz oscillator.

In order to detect these waves, Hertz employed a receiving circuit, now generally called a "resonator," of the form shown in Fig. 24, which is seen to consist of a circular loop of wire broken by a diminutive air gap at X. The radius of the loop was 35 cm., which was found by experiment to be the proper size to be in resonance with the oscillator.

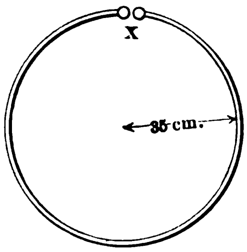

FIG. 24. Hertz's circular resonator.

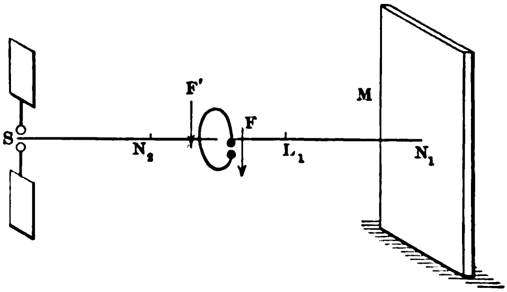

FIG. 25. Hertz's apparatus for showing the existence of electric waves in air.

To demonstrate the existence of the electric waves Hertz made use of the phenomenon of interference. The arrangement of apparatus is shown in Fig. 25. M is a metallic reflector, consisting of a sheet of zinc, 2 meters wide by 4 meters high, from which the waves sent out by the oscillator are reflected. The reflected waves superimpose upon the direct waves, producing in the region between the oscillator and the metallic reflector certain positions where the direct and the reflected waves neutralize each other and certain other positions in which their effects add. In demonstrating these effects Hertz performed a number of beautiful experiments.

In one experiment the plane of the resonator was kept parallel to the reflector, with the spark gap at the side, as shown in Fig. 25. Then wherever the resonator may be placed along the line SN_1, the electric force F and F' is the same at the two sides of the resonator. But the force F', being applied to a completely metallic part of the loop, acts to a greater advantage[1] than the force F, so that sparks are produced unless both F and F' are very small. With this orientation of the resonator, Hertz started with the resonator at N_1 close to the reflector and moved it gradually away toward the oscillator.

In the position N_1 there were no sparks in the resonator, showing that there is *a node of electric force* at the reflector. This result is consistent with the fact that a large difference of potential cannot be set up in the surface of a good conductor. As the resonator is moved away from the reflector, sparking begins in the resonator, becomes more and more lively, until a maximum is reached at L_1. This position L_1, is called *a loop of electric force.* On proceeding further in the same direction, a second minimum of sparking is found at N_2, and so forth.

Discussion of this Experiment. — The occurrence of maxima and minima in the region between the reflector and the oscillator is evidence of the undulatory nature of the disturbance, and the distance N_1N_2, or L_1L_2, is the half wave length. To make this proposition clear, reference is made to Fig. 26, which shows several drawings of the direct and the reflected wave and the resultant obtained by their superposition. The reflecting mirror is represented by the heavy vertical line at the right. The undulating line, made up of dashes, represents the direct wave, which is moving toward the reflector; and the dotted wavy line is the reflected wave, moving from the reflector. The heavy line in the

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[1] In the same way that plucking a violin string at the middle will produce a greater motion than plucking it near the end.

diagram is the resultant effect obtained by adding the two waves. The distance from one crest to the next similar crest (C_3 to C_1) is called the wave length, and the time for the wave to move one wave length is called the period T. The different diagrams, (*a*), (*b*), (*c*), (*d*), (*e*), (*f*), (*g*), (*h*), (*i*), show the conditions that exist in the region between the oscillator and the mirror at different times. At a time that we have called $t = 0$, as represented in diagram (*a*), the direct and the reflected waves are exactly opposed to each other throughout the space between the oscillator and the reflector, so that the resultant electric force is everywhere zero. In (*b*), $t = T/8$, the direct wave has moved nearer to the mirror by a distance equal to $\frac{1}{2}$ N_1L_1(= $\frac{1}{8}$ wave length), while the reflected wave, which moves with the same velocity, has moved from the mirror by an equal amount. It is seen that now the direct and the reflected waves do not oppose each other everywhere in the region. In some parts of the region, e.g., at N_1, N_2, N_3, they do oppose and

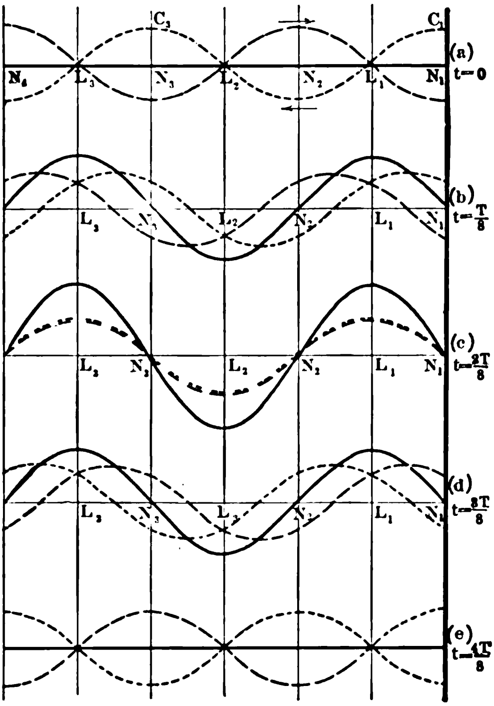


FIG. 26. Showing superposition of direct and reflected waves.

neutralize each other, while at other points their intensities add. At L_1, L_2 and L_3 the added intensities give a resultant about 1.4 times the maximum of either wave alone.

In (*c*), $t = 2\ T/8$, the direct wave has approached the mirror by another eighth of a wave length, the reflected wave has receded from the mirror by an equal amount, and the two waves exactly superpose. The resultant intensity of electric force is still zero at N_1, N_2, N_3 and N_4, while at L_1, L_2 and L_3 the intensity is double that of either wave separately.

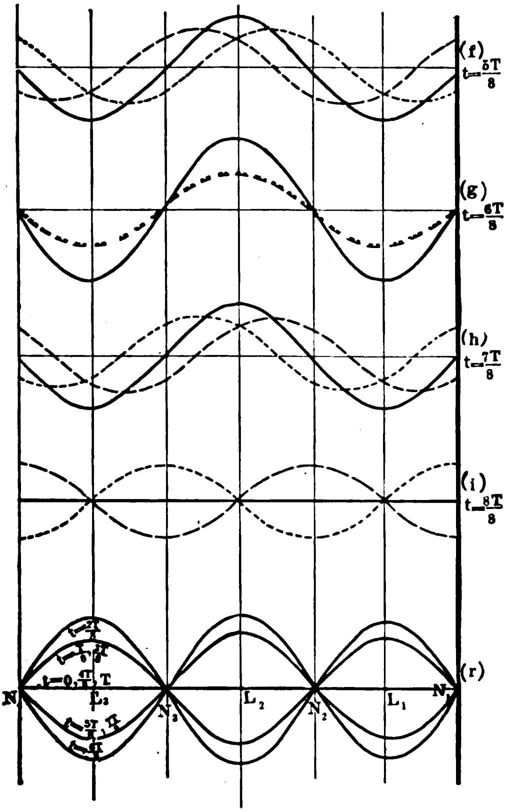


FIG. 26 (Continued).

In a similar manner the remaining drawings (*d*), (*e*), (*f*), (*g*), (*h*), (*i*) represent the progress of the direct wave toward the mirror and the recession of the reflected wave from the mirror by successive eighths of a wave length. The resultant intensity is always zero at N_1, N_2, N_3 and N_4, while, on the other hand, if we pass down the figure from the diagram (*a*) to (*h*), we see that the intensity at L_1, L_2 and L_3 begins at zero (*a*), rises to double the intensity of the single wave (*c*), falls to zero (*e*), then to minus the double intensity (*g*), and finally, at the expiration of a time equal to T, rises again to zero (*i*). To show this more clearly, all the resultants are collected in the last diagram (*r*) of the figure.

The positions N_1, N_2, N_3 and N_4 are the positions in which the resonator of Hertz gave no sparks at the detecting spark gap, because the electric force at these positions is constantly zero. The positions L_1, L_2 and L_3 are places where the sparking at the resonator was a maximum, because at these places the electric force fluctuates up and down during each period of the wave. The distance from N_1 to N_2 or from L_1 to L_2 is half the distance from C_3 to C_1, diagram (*a*), and is therefore equal to half the wave length. With the dimensions of apparatus used by Hertz in the experiment represented in Fig. 25, this half wave length was 4.8 meters.

The set of drawings given in Fig. 26 represents the conditions that exist in a " stationary wave system," in which the direct and the reflected wave are both moving, while the interference between these two waves gives a set of maxima and minima fixed in space. The minima are positions where there is never any resultant force, while at the maxima the force fluctuates between positive and negative maxima, with a period equal to T, the period of the waves.

The conditions assumed in the drawings given in Fig. 26 are somewhat simpler than the conditions actually occurring in Hertz's experiment, because the direct and the reflected waves in the case represented in the drawings are supposed to have the same amplitude, whereas in the actual experiments the reflected wave is weaker than the direct wave, so that N_1, N_2, N_3 and N_4 are not positions of zero intensity, but yet have intensity small enough to enable them to be located by the experiment.

Nature of the Wave. — The experiment by Hertz, just described, shows that the disturbance sent out from the oscillator and detected by the resonator travels as a train of waves. To give the reader an idea of the nature of this wave motion reference is made to the diagram of Fig. 27, which shows in part the electric field about the oscillator at a particular moment. This figure is a simplification of a diagram theoretically obtained by Hertz from Maxwell's equations.

The oscillator is shown in the center of the diagram, and on either side of the oscillator are shown the lines along which Maxwell's displacement currents occur. These lines are called *lines of electric induction.* We have seen in Chapter VII how we can imagine the displacement current in the dielectric to complete the conduction current in the oscillator. In that case the lines of electric induction terminate on a positive and a negative charge at their two ends. At the instant represented in the diagram, the two halves of the oscillator have opposite charges, and some of the lines of electric induction near the oscillator terminate upon the charges on the oscillator. But a little farther out from the oscillator the lines in the diagram are represented as closed upon themselves. This closing of a loop on itself occurs when the positive and the negative charges on the oscillator come together as the current in the oscillator reverses. The closed loops represented in the diagram have been produced by successive oscillations of the current on the oscillator, and have been liberated from the oscillator and are moving freely away. The condition of things in the space around the oscillator in action may be pictured to the mind by supposing that these closed loops of electric induction move away from the oscillator, and as they move they elongate and grow less intense. Their width, however, remains constant, so that if a receiver be placed in any fixed position, say in the equatorial plane, *PP*, the inductive action of the loops, as they successively pass, changes continuously from one direction to the other with a period equal to that of the oscillator. This train of continuously reversing electrostatic induction is one aspect of the electric-wave train.

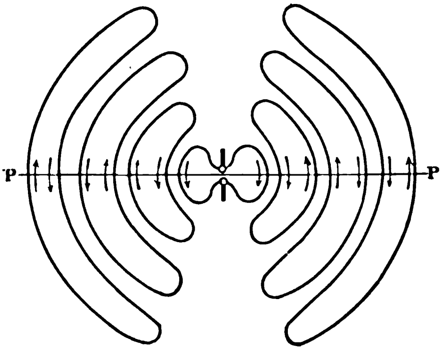


FIG. 27. Simplified diagram of electric force about an oscillator.

Another aspect of the electric wave train may be discovered by examining the magnetic field about the oscillator. The lines of magnetic force about the oscillator are circles in a plane perpendicular to the oscillator, and these lines in a non-magnetic medium are everywhere perpendicular to the lines of electric induction, so that the receiving circuit, placed, for example, in the equatorial plane, experiences also a series of continuously varying magnetic forces which tend to induce an electromotive force in the receiving circuit in the same direction as that induced by the electric induction, so that both the electric and the magnetic effects act together and are called the components of the electric wave. One component is *electric induction,* which is in the plane of the oscillator. The other component is *magnetic force,* which is perpendicular to the electric induction. Both of these components are perpendicular to the direction of propagation of the wave; that is to say, the wave is transverse.

Attempt to Determine the Velocity of the Wave in Air. — Hertz attempted to determine the velocity of the wave. We have seen that he found the wave length, λ, to be 9.6 meters. This is the distance traveled by the wave during the period of one oscillation of the current in the oscillator, so that, if we knew the period, T. we could calculate the velocity by the equation $v = \lambda / T$. Hertz attempted to obtain the period, T, of the oscillator by calculation from such formulas as could be had for oscillators of this shape, and he obtained the period of complete oscillation to be 2.8 hundred-millionths of a second. This gave for the velocity of the waves the value 340,000 kilometers per second. In this calculation, as Professor H. Poincaré pointed out, Hertz made an error, and overestimated the period in the ratio of $\sqrt{2} : 1$, so that, with this correction, he would have obtained the velocity of the waves to be 480,000 kilometers, while the velocity of light is 300,000 kilometers per second. This apparent discrepancy between the experiment and Maxwell's theoretical conclusion, that the velocity of the waves is equal to the velocity of light, was due, as Hertz suggested, to the inapplicability of the formula used in the calculation of the period of oscillation. Experiments which we shall soon come to discuss show that the velocity of the electric waves is the same as the velocity of light, and thus confirm Maxwell's predictions.

CHAPTER IX

EXPERIMENTS ON THE IDENTITY OF ELECTRIC WAVES AND LIGHT

Hertz's Apparatus for Shorter Electric Waves. — After Hertz had succeeded in proving that the action of an electric oscillation spreads out as a wave into space, he planned experiments with the object of concentrating this action and making it perceptible to greater distances, by putting the oscillator in the focal line of a large concave cylindrical mirror. In order to avoid the disproportion between the length of the waves and the dimensions he was able to give to the mirror, Hertz made the oscillator smaller, so that the length of the waves was less than one-tenth of those first discovered.

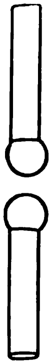


Fig. 28. Hertz's rectilinear oscillator.

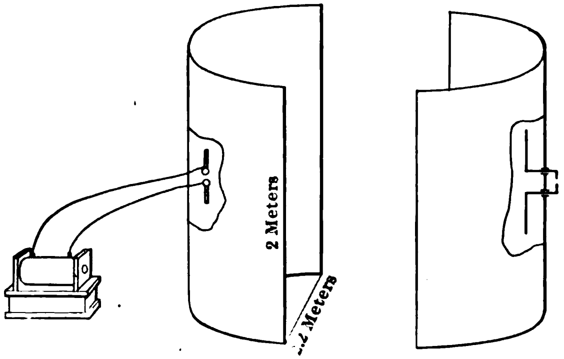


Fig. 29. Hertz's cylindrical mirrors. Oscillator is at left; resonator, at right.

The form of oscillator used in these experiments is shown in Fig. 28. The two halves of the oscillator were cylindrical bodies 3 cm. in diameter, terminating in spheres 4 cm. in diameter. The total length of the oscillator was 26 cm., and the spark gap was usually about 3 mm.

For a receiving circuit, the circle of wire used in the previous experiments was replaced by a linear resonator, consisting of two straight pieces of wire, each 50 cm. long and 5 mm. in diameter, adjusted in a straight line so that their near ends were 5 cm. apart.

From these ends two wires, 15 cm. long and 1 mm. in diameter, were carried away parallel to each other to a micrometer spark gap similar to that used for indicating the waves in the previous experiments.

The method of mounting the oscillator and resonator in the focal line of the cylindrical mirrors is shown in Fig. 29. The reflecting surface of the cylindrical mirrors was of thin sheet metal. The dimensions of the reflectors are shown in the diagram. With these reflectors about the oscillator and the resonator Hertz was able to get indications of waves up to a distance of 20 meters. The length of the wave, measured by the method of the last experiment, was 66 cm., and the period of oscillation, assuming that the waves travel with the velocity of light, was 2.2 thousandths of a millionth of a second. With this wave length Hertz succeeded in carrying out many of the elementary experiments that are commonly performed with light.

Rays and Shadows. — With the electric waves, as with light and radiant heat, shadows may be cast by objects opaque to the waves.

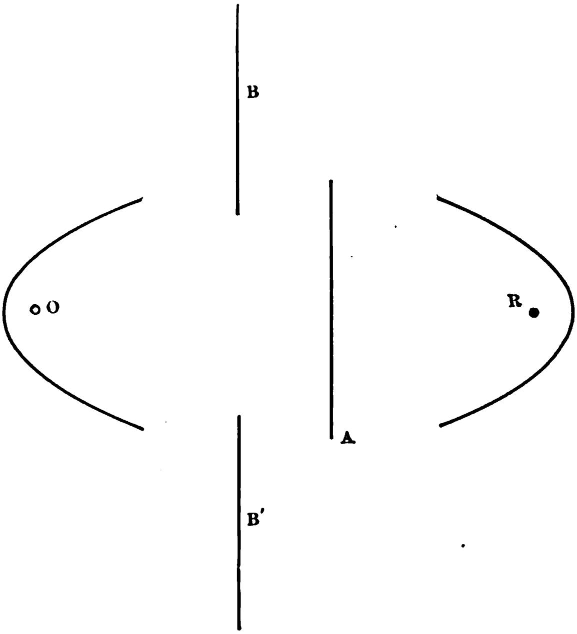


FIG. 30. Plan of oscillator, receiver and metallic screens.

Hertz found that a metallic screen interposed between the oscillator and the receiver, in the position *A*, Fig. 30, stopped the sparking of the resonator completely, while the two screens in the position *B* and *B'* did not materially diminish the sparks at the resonator. If, however, the opening between *B* and *B'* was made narrower, the sparks became weaker, and disappeared when the opening was reduced below a half meter. In experiments of this kind, although the dimensions of the screens are measured in meters, these screens are yet not large in comparison with the wave length of the waves, and the phenomena of diffraction are very marked, so that there is no sharp geometrical limit either to the rays or to the shadows.

Polarization. — Hertz showed that the electric waves produced by his linear oscillator are *polarized waves.* One way employed by him for showing this was to start with the focal lines of the two reflectors parallel, as in Fig. 29, so that there is lively sparking at the resonator, and turn the receiving mirror about the line joining oscillator and resonator. During this operation the resonator sparks become more and more feeble, and when the two focal lines are at right angles, as in Fig. 31, no sparks whatever are obtained at the resonator, even when the two mirrors are moved up close to each other.

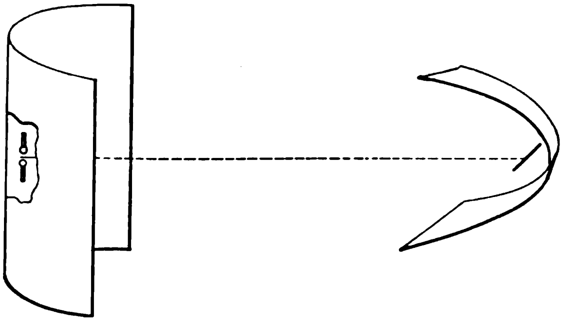
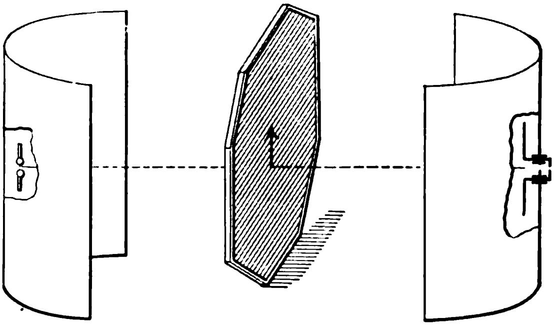


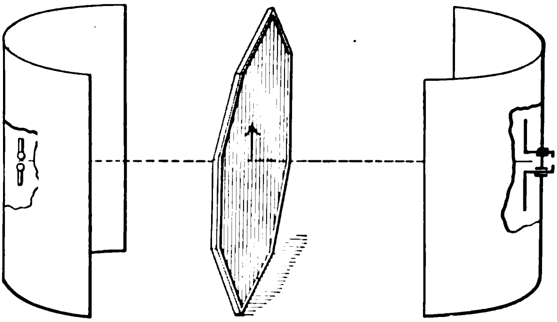
FIG. 31. Showing polarization by the absence of effects when the oscillator and the resonator are at right angles to each other.

In another method of showing that the electric waves are polarized, Hertz made use of a grating of wires. The wires of the grating were 1 mm. in diameter and 3 cm. apart, and were mounted in an octagonal wood frame 2 meters high and 2 meters long. When the grating was interposed between the oscillator and the resonator so that the direction of the wires of the grating was perpendicular to the oscillator and the resonator, as shown in Position 1, Fig. 32, the screen practically did not interfere at all with the sparks at the resonator. But if the screen was set up in such a way that its wires were parallel to the oscillator and the resonator (Position 2, Fig. 32) it stopped the rays completely. With regard, then, to the transmission of energy the screen behaves toward the electric waves as a tourmaline plate behaves toward a plane polarized ray of light.

Another way of showing polarization of the electric waves was also devised by Hertz. The receiver was again placed so that its focal line was perpendicular to that of the oscillator, as in Fig. 31. Under these circumstances, as already mentioned, no sparks appeared. Nor were any sparks produced when the screen was interposed in the path of the waves, so long as the wires of the screen were either horizontal or vertical. But if the frame was set up in such a position that the wires were inclined at 45° to the horizontal on either side (see Fig. 33), then the interposition of the screen immediately produced sparks at the resonator spark gap. Clearly the screen resolves the electric force of the advancing wave into two components, and transmits only that component which is perpendicular to the direc-



Position 1 Transparent



Position 2 Opaque

Fig. 32. Polarization proved by the interposition of a grating of wires.

tion of its wires. This component is inclined at 45° to the axis of the receiver, and so has a component along the direction of the resonator.

From these experiments it is evident that the interposition of the screen stops the waves when the wires of the screen are parallel to the *electric* component of the waves. It is in this position that the electric force would produce currents in the wires. The changing magnetic force at right angles to the wires would also produce currents in the wires, so that both the components, that is to say, the whole electric wave, would be absorbed or reflected. Hertz showed that the action was one of reflection rather than of absorption; in this the wire screen differs from the action of the tourmaline crystal on light, for the extinguished component in that case is absorbed rather than reflected.

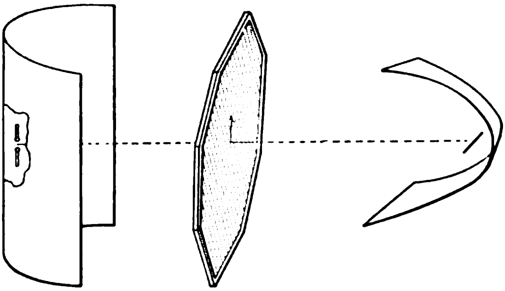


FIG. 33. Rotation of plane of polarization by a wire grating at 45°.

Refraction. — Hertz also performed some experiments on the refraction of electric waves, employing for the purpose a large prism of pitch cast in a wooden box. The base of the prism was an isosceles triangle 1.2 meters on the side, and with a refracting angle of

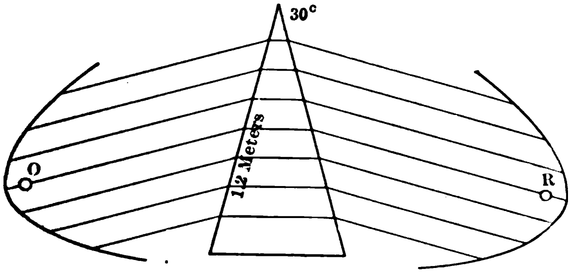


FIG. 34. Showing refraction of electric waves by prism.

nearly 30°. The height of the prism was 1.5 meters, and its weight was 1200 pounds. With the arrangement of apparatus as shown in Fig. 34 the rays were refracted by the prism through an angle of 22°. From this value Hertz calculated the index of refraction of the pitch to be 1.69, while the refractive index of pitch-like materials for light is given as being between 1.5 and 1.6.

In concluding this series of experiments Hertz says: "We have applied the term rays of electric force to the phenomena which we have investigated. We may perhaps further designate them as rays of light of very great wave length. The experiments described appear to me, at any rate, eminently adapted to remove any doubt as to the identity of light, radiant heat, and electromagnetic wave motion. I believe that from now on we shall have greater confidence in making use of the advantages which this identity enables us to derive both in the study of optics and of electricity."

Experiments of Righi. — Immediately following the discovery of electric waves by Hertz, a great number of experiments were made by various investigators in repetition of Hertz's expermients and in the effort to extend his results, particularly in the direction of the study of the properties of short electric waves, so as to obtain a further comparison of their properties with the properties of light. In order to obtain electric waves shorter than those of Hertz, Professor Righi [1] of the University of Bologna devised an oscillator consisting of two spheres (*B*, *C*, Fig. 35) separated by a small spark gap in oil. *A* and *D* are the terminals of an induction coil or electric

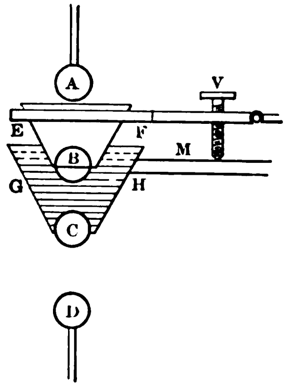


FIG. 35. Professor Righi's oscillator for short electric waves.

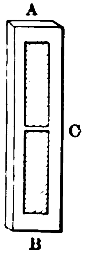


FIG. 36. Righi's resonator.

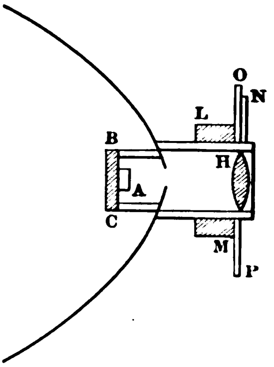


FIG. 37. Mounting of Righi's resonator.

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[1] Augusto Righi: L' ottica delle Oscillazioni Elettriche, Bologna, 1897.

machine used to charge the oscillator. These terminals are provided with the spheres A and D, which are separated from the spheres B and C of the oscillator by spark gaps in air, so that the oscillator BC is without metallic connection with the other parts of the circuit. The spheres B and C were fastened with shellac into the truncated cones of glass EF and GH, which were supported in an ebonite frame. The lower funnel-shaped glass vessel served to contain the oil. The spark length in oil between B and C could be regulated by the screw V. The advantage of having the spark between the spheres take place in oil instead of in air, as had already been pointed out by MM. Sarasin and De la Rive, arises from the fact that it takes a greater difference of potential to start a given length of spark and therefore gives a more energetic discharge. When the spark is once started, the oil is carbonized and becomes conducting, so that the succeeding oscillations pass with comparatively little damping. Also the oil obviates the necessity of repeatedly polishing the terminals, as Hertz found he had to do when he attempted to get short waves with the spark in air. Righi found that vaseline oil is especially well adapted for use with his oscillator.

For a receiving apparatus Righi made use of a resonator consisting of a strip of silver AB deposited on glass and interrupted by a diamond scratch C across the middle of the strip. This provided an extremely short spark gap between the two parts of the resonator, as shown in Fig. 36. Also the spark across this small gap will occur more easily than a spark of equal length in free air.[1] Righi's resonator is thus seen to be an extremely sensitive modification of the rectilinear resonator used by Hertz.

In most of Righi's experiments the oscillator and the resonator were mounted in cylindrical reflectors. The mounting of the resonator is shown in section in Fig. 37. The resonator is at A, and is fastened upon a strip of ebonite BC. The observer looks through the converging lens at H, which serves to magnify the minute sparks between the two halves of the resonator. The apparatus could be used quantitatively by observing the angle through which it was necessary to turn the resonator and its reflector in the support LM in order to extinguish the sparks. The angle of turning was indicated by the pointer N moving over a graduated circle OP.

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[1] The author has shown that the potential required to start a spark along a surface of glass is about .44 of the potential to start a spark of equal length in free air. (Pierce: Physical Review, Vol. 2, p. 99, 1894.)

The following table gives the dimensions of Righi's apparatus and the corresponding wave lengths obtained:

Denomination of the apparatus.	Oscillators.	Resonators.		Wave length in cm.
	Diameter of the spheres.	Length in cm.	Width in cm.	
I.	.8	0.9	.1	2.6
II.	3.75	3.6	.2	10.6
III.	8.0	10.	.2	20.
		3.6	.6	11.8
		10.	.6	21.4

In a test of the sensitiveness of various combinations of this apparatus, Righi found that with the resonator III and the oscillator II both armed with their respective cylindrical reflectors, sparks appeared across the minute diamond scratch of the resonator when it was at a distance of 25 meters from the oscillator. This is a distance of 125 times the wave length for this apparatus. With the oscillator III, the sparks were evident at a greater distance. With resonator II and oscillator II, the greatest distance to which indications of the waves could be obtained was 20 meters, which is 190 times the wave length. While with the minute apparatus, resonator I and oscillator I, the maximum distance was about 80 centimeters, which is 31 wave lengths. With this smaller apparatus, in spite of the comparative feebleness of the waves, many experiments that are commonly performed with light waves could be successfully carried out with the electric waves. For example, a small coin (10 centesimi) can be used to reflect the waves. The coin does not need to be polished as with experiments on the reflection of light, because irregularities of the surface of the coin are too small to have any effect on the reflection of the electric waves. Refraction and total internal reflection of these short waves could be shown with prisms of sulphur or paraffin that were very little larger than the glass prisms used in optics.

Righi also succeeded in demonstrating the double refraction and elliptic polarization of the waves by slabs of the wood of the fir tree.

The Use of a Thermal Junction for Measuring Electric Waves. — In the experiments of Hertz and Righi the presence of the electric waves was manifested by the production of sparks across a minute spark gap between two parts of the receiving conductor. In 1892

Ignaz Klemenčič [1] showed that a thermal junction could be employed to detect and measure the waves. Klemenčič's device, Fig. 38, consists of two thin sheets of brass *MM*, 10 cm. broad and 30 cm. long, placed 3 cm. apart, and having soldered to them respectively a very fine platinum and a very fine platinum-nickel wire, which were crossed at *k* and were thence conveyed off at right angles and soldered at their other ends to the leads *l*, *l* of a sensitive galvanometer. This resonating system was fixed at the focal line of a suitable cylindrical metallic reflector. When electric waves, with the electric force parallel to *MM*, fall on this receiver, electric oscillations between *M* and *M* produce heating of the knot *k*, which is the point of contact of two dissimilar metals, and in consequence the heat developed gives rise to a thermoelectromotive force at the knot and consequently to a current in the galvanometer. By the use of this instrument and a Righi oscillator, Klemenčič has studied the reflection of electric waves from metals and insulators.

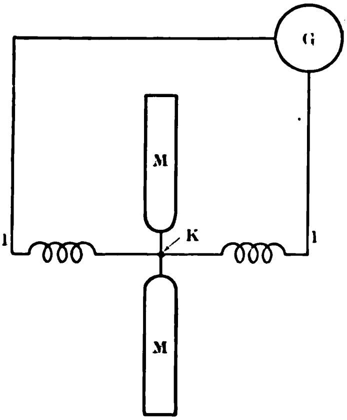

FIG. 38. Resonator employing thermal junction.

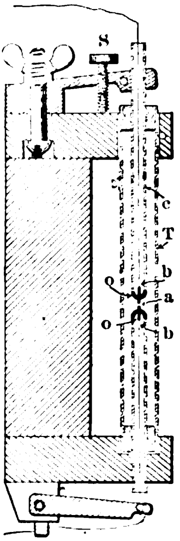

FIG. 39. Oscillator for very short electric waves.

Various investigators have made use of the Klemenčič thermal junction in quantitative experiments on electric waves. By reducing the size of the metal vanes *MM*, Professor A. D. Cole [2] has applied the apparatus to measurements with waves with a wave length of 4 cm. Professor Lebedew,[3] employing a slightly different form of

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[1] Ignaz Klemenčič: Wied. Ann., 45, p. 62, 1892.

[2] A. D. Cole: Wied. Ann., 57, p. 290, 1896, and Phys. Review, 7, Nov., 1898.

[3] Peter Lebedew: Wied. Ann., 56, p. 1, 1895.

thermal junction, worked with waves of wave length of only 6 mm., and succeeded in showing the double refraction of electric waves by crystals. A form of oscillator similar to that used by Cole and by Lebedew for producing their short electric waves is shown at *o, o*, Fig. 39.

Professor Lampa and Professor Bose have also succeeded in making measurements with electric waves of only 6 mm. wave length.

Wave Length of Electric Waves and Light. — The following table contains in round numbers the value of wave length and number of vibrations per second of some electric waves and waves of radiant heat and light:

Electric waves produced by	Wave length in cm.	Number of vibrations per second.
Commercial Alternating Current	200,000,000	150
Leyden Jar Discharge, Feddersen	300,000	100,000
Hertz's First Oscillator	1,000	30,000,000
Hertz's Rectilinear Oscillator	60	500,000,000
Righi's Oscillator	2.6	11,000,000,000
Lebedew, Lampa, and Bose's El. Waves	.6	50,000,000,000
Longest Radiant Heat	.01	3,000,000,000,000
Orange-colored Light	.00006	500,000,000,000,000
Shortest Ultra-violet, Schumann, Lyman	.00001	3,000,000,000,000,000

Physicists have long been accustomed to recognize that the difference between radiant heat, visible light, and the actinic ultra-violet radiation is merely difference in wave length, and that our greater familiarity with the visible portion of the spectrum arises merely from the fact that we have a particular set of nerves sensitive to these rays.

The visible part of the spectrum lies between wave lengths .000040 and .000076 centimeter. By the aid of the thermopile and the photographic plate the spectrum has been extended to include all the radiation with wave length between .00001 (extreme ultra-violet) and .01 centimeter (extreme infra-red). This upper limit is about 1000 times the lower limit. It is interesting to note that the Hertzian waves measured by Lebedew, Lampa, and Bose have a wave length only about 60 times the wave length of the limit attained in the infra-red. That is to say, the shortest Hertzian waves that have been measured are nearer in wave length to the longest measured heat waves than these are to the shortest measured ultra-violet. Also *in properties* the Hertzian waves are nearer to the long heat radiations than these are to the ultra-violet or even to the visible. For example, some of the long heat waves, like the Hertzian waves, pass readily through vulcanite and other insulators opaque to visible light.

Space is lacking to consider further the experimental evidence in favor of Maxwell's proposition that electric waves are of the same nature as light waves, and that the light waves are in fact simply electric waves of those particular wave lengths that possess the property of being capable of affecting the retina of the eye.

CHAPTER X

ON THE PROPAGATION OF ELECTRIC WAVES ON WIRES

Wheatstone's Experiments. — Early in the history of the electric telegraph the question arose as to the velocity of propagation of electric disturbances along wires. The first attempt to measure this velocity was made by Wheatstone[1] in 1834. Wheatstone attempted to measure the velocity of electricity in a circuit consisting of a copper wire about half a mile long, and extended back and forward so as to form twenty parallel lines, 15 cm. apart. Three spark gaps were inserted in this line, one at each end and one at the center. These were arranged horizontally, side by side, in front of a mirror mounted on a horizontal axis and capable of being revolved at the rate of 800 revolutions per second.

Upon discharging a condenser through the two end spark gaps into the circuit, the image of all three of the sparks could be seen in the revolving mirror, and the image of the central spark was found to be displaced with reference to the other two, showing that the central spark occurred later than the two end sparks. The amount of the displacement of the central spark, together with the speed of the mirror, furnished the data for computing the speed of propagation of the electric current. Wheatstone had difficulty in determining the amount of the displacement, which he could obtain only by eye observations. Computations from Wheatstone's observations seemed to show that an electric discharge traversed the copper wire at a speed of 288,000 miles (463,000 kilometers) per second, which is greater than the velocity of light; and this was long accepted as the true "velocity of electricity."

While the numerical result obtained by Wheatstone is now known to be incorrect, the experiment is yet interesting in that it showed that time was required for the electrical disturbance to traverse the wire. The revolving mirror employed in this experiment has now become a classical apparatus in physical investigation.

Other Early Experiments. — In 1850 Fizeau and Gounelle likewise made a series of experiments on the velocity of the electric

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[1] Wheatstone: Phil. Trans., Part II, p. 583, 1834; Pogg. Ann., 34, p. 464.

current, and for this purpose availed themselves of the telegraph lines between Paris and Amiens (314 kilometers) and between Paris and Rouen (288 km.). Their measurements gave a velocity of 101,700 km. per second for iron wires, and 172,000 km. per second for copper wires.

In other similar measurements of the apparent velocity of the electric current various results have been obtained in practice which are much lower than those of Wheatstone, and Fizeau and Gounelle, being in some cases 2240 kilometers per second, and in others 4800, 28,000, 96,000 and so on. What, then, is the explanation of this great variability in the experimental results?

Theoretical Discussion. — In 1855, in discussing the feasibility of an Atlantic cable, Sir William Thomson gave a mathematical treatment of a case of the propagation of electric disturbances in conductors. In 1857 Kirchhoff, and in 1876, Heaviside, developed extended theoretical treatments of the problem. The results obtained by these mathematical physicists show that the velocity of propagation of electrical disturbances in conductors depends on the nature of the disturbance and the relative values of the capacity, self-inductance and resistance of the conductor.

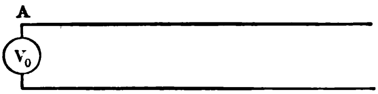

Fig. 40. Two parallel wires with applied electromotive force.

If we have two long parallel wires (Fig. 40) as in the case of land telegraph and telephone lines, or one wire in an insulating sheath submerged in a conducting body, as in the submarine cable, three important cases arise in practice.

Case I. Telegraphy. — If the self-induction of the line is negligible in comparison with its resistance and we have an electromotive force impressed on one end of the line, the current in the conductor grows in a manner described as "diffusion." Fig. 41 gives a set of curves [1] showing the difference of potential between the two conductors at various positions along the line, at different times after the application of the electromotive force. In this case there is no proper velocity of the electricity; for at the instant the battery is applied some electricity appears all along the line, and the charge at a short distance from the origin grows faster than the charge at a greater distance. This is approximately the case that occurs in submarine

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[1] Redrawn from Professor A. G. Webster's Electricity and Magnetism; Macmillan, 1897.

cabling, and Sir William Thomson showed that in the case of the proposed Atlantic cable, the time required for each signal would be sixteen times as long as the time for a cable of the same cross section

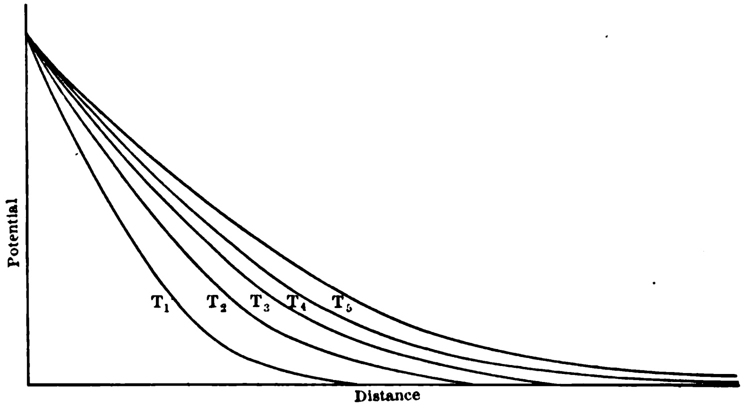

FIG. 41. Diffusion of electric current in parallel wires with negligible inductance.

with one-quarter of the length, such as then existed in the French submarine telegraph to Sardinia and Africa.

The condition assumed by Sir William Thomson is only approximately realized in practice, for in no line is the action of self-induction

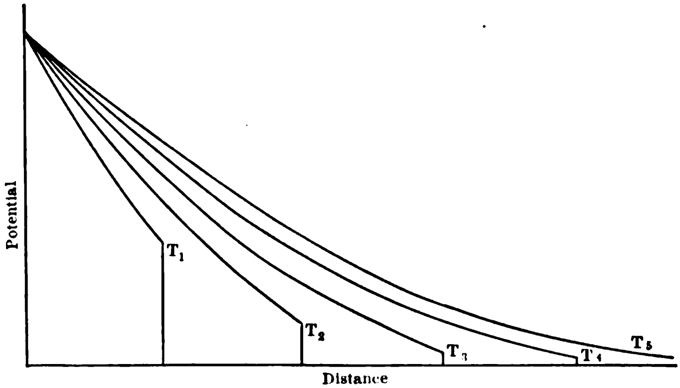

FIG. 42. Modified diffusion.

completely negligible. Especially is the action of the self-induction not negligible at the instant of applying the battery at A, Fig. 40, because this application of the battery is sudden, and for a sudden charging of the conductor the effect of the self-induction is greater than for a slow application of the charge. For this reason the propagation of the disturbance is more accurately represented by the set of curves given in Fig. 42. In this diagram it is seen that the disturbance has a nearly square wave front, which, according to the theory, travels with the velocity of light, while succeeding parts of the impulse lag more and more behind the wave front. The square wave front itself becomes also more and more attenuated as the disturbance progresses along the wires.

This same condition of things exists to some extent in the case of land telegraph lines, and accounts for the indefiniteness of the results that have been obtained in the attempt to measure the velocity of propagation. If for a particular length of line the apparatus used by the experimenter for detecting the wave is sufficiently sensitive to respond on the arrival of the wave front, the value obtained for the velocity is the velocity of light; while with a greater length of line the wave front is too feeble to affect the instrument, which then responds to a more intense part of the wave arriving later, and hence gives a smaller value for the velocity.

Case II. Telephoning.— Suppose, now, that instead of simply applying a battery to the line, as in telegraphing, we apply a *telephonic* electromotive force to the parallel wires of Fig. 40 or to the submarine cable. This telephonic electromotive force is an alternating electromotive force. Although the self-inductance and resistance of the circuit may be the same as before, the effect of the self-induction is larger in the telephonic case, because of the rapidity of the alternations of the electromotive force at the source. Under this condition Heaviside finds that the different waves generated by the sounds of different pitch travel with different velocities, and that this results in a distortion of the wave and puts a limit to the distance to which the telephone can be used. This distortion is caused by the resistance and capacity of the line, and is partially eliminated by self-induction. Heaviside says that this "self-induction is the telephonist's best friend," for it tends to preserve the sharpness of the wave and to eliminate the part of the disturbance lagging behind the wave front. Heaviside pointed out that the addition of properly distributed self-induction was *beneficial* to prevent distortion in telephony; and in actual practice, by adding inductance coils at intervals along telephone lines, Professor Pupin has considerably increased the distance to which distinct speech may be transmitted.

In the case of the submarine cable, on account of the relatively small value of the self-inductance, submarine telephony is not at present practicable to a greater distance than about twenty miles (32 kilometers).

Case III. Electric Waves of High Frequency. — As a third case, which is the one in which we are here chiefly interested, let us suppose that the electromotive force applied to the end of the two parallel wires oscillates with very great frequency. The *effect of the resistance then becomes negligible* in comparison with the effect of the self-induction. The theoretical treatment of this case shows that such a disturbance travels with the velocity of light, and except by a decrease of amplitude, the wave is not distorted during its progress along the wires. In what follows we shall see how experiments have confirmed this deduction from the theory.

Hertz's Experiments with Waves on Wires. — In 1888, a short time before his experiments with electric waves in air, which have been described in chapters VIII and IX, Hertz performed a series of experiments with electric waves on wires. The form of apparatus employed is shown in Fig. 43. At a short distance behind one of the plates A of the oscillator, a second plate P was placed. From P a copper wire was bent through the arc mn and thence led off horizontally. When the plate A is charged positively, negative electricity is attracted to the nearer side of the plate P, and an equivalent positive charge is sent away along the wire. When the charge on A becomes negative, a similar negative charge moves away along the wire, so that during the oscillations between A and A', in which the charge on A changes continuously back and forth from positive to negative values, a train of positive and negative impulses, constituting a train of waves, travels out along the wire.

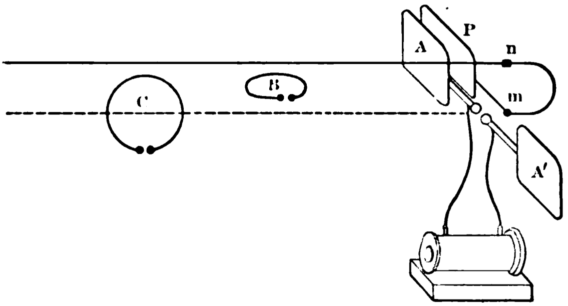

FIG. 43. Hertz apparatus for waves on wires.

The train of waves on the wire will be reflected from the end of the wire, as may be seen from the following reasoning. The current cannot flow past the end of the wire, nor does the electricity constituting the current merely flow out to the end of the wire and stop in a state of equilibrium. Two forces are acting on the current: (1) the accumulation of electricity near the end of the wire raises the potential of the wire and provides a force opposing the current; (2) the slowing down of the current causes change in the magnetic field surrounding the wire, and this tends to prevent the cessation of the current. These two forces do not act together,—when one is a maximum, the other is a minimum. As a result first one and then the other of these forces will predominate, so that the charge will first be sent into the parts near the end of the wire by the magnetic field (self-induction) and will then be sent out again by the electrostatic rise of potential (reciprocal of capacity). The effect of this is that the periodically arriving impulses will be sent back again with the same period, and we shall have, therefore, a direct and a reflected train of waves. The direct and the reflected waves will interfere with each other, so as to form a stationary system of waves like that obtained in the experiment with waves in air reflected from a sheet of metal (Chapter VIII). In this case, however, the end of the wire will be a loop of potential; whereas the metal reflector of the waves in air is a node of potential. There is also another difference; for in the case of the wire, the returning wave will again be reflected at *P*, and a simple stationary wave system can only be realized provided the horizontal wire has a proper length, which may be determined by experiment.

Hertz studied the waves produced in the wire, with the aid of his circular resonator, shown in the figure. With the resonator in the vertical position *C*, Hertz was able to locate the nodes and loops of current in the wire by the absence or presence of sparks at the resonator. When, however, the resonator was placed in the horizontal position *B*, the effect obtained was due partly to the waves in the wires and partly to a linking with the resonator of magnetic lines directly from the oscillator. The compound effect obtained in the latter case was utilized by Hertz in a study of the interference between the waves in the wire and the waves in the air. He came to the conclusion that the wave length, and consequently the velocity of propagation, was different in the two cases. This was in contradiction of Maxwell's theory.

Later, by the use of a smaller oscillator at *AA′*, he found that the difference between the velocities of the waves on wires and in air very nearly disappeared.

Experiments of Sarasin and De la Rive. — While Hertz was puzzling over this problem, and attempting to explain the discrepancy between his experiment with the long waves, which did not agree with Maxwell's theory, and his experiment with the shorter waves, which did agree with the theory, MM. Sarasin and De la Rive at Geneva repeated the experiment with the longer waves in a room larger than that available to Hertz, and obtained from this case also approximately the same velocity for the waves on the wire and the waves in air. Hertz's difficulty probably arose from the disturbing influence of electric waves reflected from objects in the room. Maxwell's proposition of the equality of the two velocities is strictly true only provided the waves on wires are produced on two parallel wires close together, — a positive impulse being started along one of the wires and at the same time an equal negative impulse being started along the other wire. Introducing this precaution, numerous subsequent experimenters have confirmed Maxwell's conclusion that the velocity of the electric waves in a pair of nonmagnetic, conducting wires is the same as the velocity of these waves in the dielectric surrounding the wires.

Direct Determination of the Velocity of the Waves on Wires. — Blondlot,[1] Trowbridge and Duane,[2] and Saunders[3] have made direct experimental determinations of the velocity of electric waves on wires. In all of these experiments the method consisted in determining the wave length λ of the waves on the wires, and in determining independently the time of the oscillation T that produced the waves. The quotient obtained by dividing the wave length by the time of oscillation gives the velocity $\left(\frac{\lambda}{T} = v\right)$; for the wave length is the distance traveled in the time of one oscillation, and dividing the distance traveled by the time required to travel it gives the velocity. In all of the experiments the wave length λ was determined by exploring the stationary wave system on the wires by a method like that devised by Lecher (p. 70). Trowbridge and Duane and Saunders determined the period of oscillation T by spark photographs taken with the aid of the revolving mirror, while Blondlot determined the period by

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[1] Blondlot: Comptes Rendus, Vol. 117, p. 543, 1893.

[2] Trowbridge and Duane: American Journal of Science, Vol. 49, p. 297, 1895.

[3] Saunders: Physical Review, Vol. 4, p. 81, 1896.

a resonance method, like that at the present day used in getting the wave length in a wireless telegraph antenna.

The following results were obtained for the velocity of electric waves on wires:

Observer.	Velocity in kilometers per second.
Blondlot	293,000 298,000
Trowbridge and Duane.	298,800 300,300
Saunders	295,400 299,400 299,800 299,800 299,500 299,900

The average of the best determination of the velocity of light is about 299,900 kilometers per second, with which the above determinations of the velocity of the electric waves on copper wires is in good agreement.

Velocity of Electric Waves in Air. — Although the velocity of the electric waves in air has not been determined by a direct method, the experiment of Sarasin and De la Rive showed that the velocity of the waves in air is the same as their velocity in copper wires surrounded by air, and therefore the same as that of light.

Waves on Iron Wires. — On account of the magnetic properties of iron, the velocity of the waves on small iron wires has been found to be slightly less than the velocity of waves of the same period on a nonmagnetic metal like copper. With wires ½ millimeter in diameter and with 115,000,000 oscillations per second, St. John found that the velocity on the iron wire was 4 to 5% less than the velocity on the copper wires. This result showed that the magnetization of the iron is able to follow extremely rapid reversals of the magnetizing current.

On Surface Travel. — In addition to this slight change in velocity due to the magnetic property of the iron, the damping effect of the resistance of the iron is very large. In attempting to estimate the effect of resistance on the damping of oscillations of high frequency, it should be remembered that these rapid currents travel in a very thin film on the outside of the conductor. By electrolytically coating an iron resonator with copper and a copper resonator with iron, Bjerknes found that when this coating was greater than a hundredth of a millimeter, the coated iron resonator acts like one of copper and the coated copper resonator like one of iron. This showed, in the case of electric oscillations of very high frequency, that the currents are confined to a shell whose thickness is of the order of a hundredth of a millimeter. The thickness of this shell depends, however, on the frequency of the oscillations, and on the radius and material of the conductor. (See Appendix II.)

Waves on Wires Studied with a Vacuum Tube Detector. — A form of apparatus devised by Professor Lecher for showing the existence of stationary waves on wires is shown in Fig. 44, which is a view of the apparatus from above. *A′FA* is an ordinary Hertz oscillator. Parallel to the plates *AA′* of the oscillator are placed two equal plates *BB′* connected to a pair of parallel horizontal wires. A bridge of wire, shown in a separate drawing at the right, and having an insulated handle, may be placed across the horizontal wires. A Geissler tube *gg′*, which is pumped to a sensitive vacuum, is placed across the wires near their outer end, so that the glass of the tube rests on the wire. When the oscillator is in action, the Geissler tube will glow. Let us now put the bridge across the wires near the Geissler tube, the glow will cease, because it is short-circuited by the bridge. If now we move the bridge toward the oscillator, a position will be found, *XX′*, for which the Geissler tube at the ends of the wires will again light up into a lively glow. A slight motion of the bridge in either direction from this position causes the glow to diminish. In explanation of this phenomenon we must think of the wires as divided into two circuits by the bridge. One of these circuits, which we will call the "oscillator circuit," is *FABXX′B′A′F*, comprising the two condensers *AB*

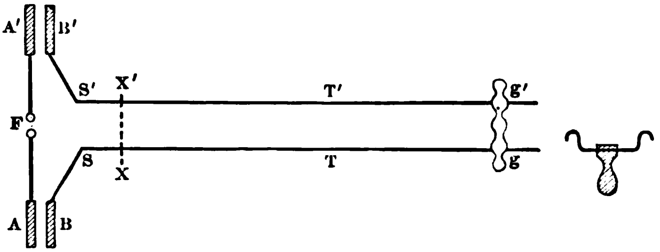

FIG. 44. Lecher apparatus.

and $A'B'$ and the spark gap F. This circuit has its own definite period of oscillation. The other circuit, which we will call the "resonator circuit," consists of the conductors $gXX'g'$. When the bridge XX' is in the position that causes the Geissler tube to glow, the oscillator circuit and the resonator circuit are in resonance, and during one complete oscillation the electric wave goes from the bridge out to g', back across the bridge, out to g, and back again to the bridge. Whence it is seen that the length of the conductor from g' across the bridge to g is the half wave length of the oscillator.

If now the bridge is moved from XX' toward the oscillator, a second position SS' of the bridge is found for which the tube is caused to glow. During this displacement of the bridge, the self-inductance, and therefore the period, of the oscillator circuit is diminished, while the length of the wire to the right of the bridge is increased. Therefore, the wire to the right of the bridge cannot be in resonance, as a whole, with the oscillator circuit. We can show this experimentally, for if we leave the first bridge at SS' and place a second bridge across the wires, a position TT' can be found for which the presence of the second bridge does not affect the glow of the tube. A slight motion of the second bridge to the right or to the left diminishes the glow.

The two positions SS' and TT' are called nodes of electric potential. In a similar way with longer parallel wires several nodes may be located. The free end of the wires is always a loop of potential, and other loops of potential exist halfway between the nodes. The presence of these nodes and loops at equal intervals along the parallel wires shows the existence of a stationary wave system similar to that discovered by Hertz in his experiments with electric waves in air.

Blondlot's Apparatus. — A modification of Lecher's apparatus made by Professor Blondlot is shown in Fig. 45. The two halves of the oscillator are here bent into semicircles, while the parallel wires lead out from a secondary circuit placed immediately beneath the oscillator. The oscillator and the circular portion of the secondary are submerged in a glass vessel containing oil. Leads from the induction coil are brought into the oil and connected to the two sides of the spark gap, — one connection being made directly at a and the other connection being through a small spark gap at b. In this form of apparatus the waves on the wires are produced by electromagnetic induction from the oscillator.

Arons' Tube. — A very beautiful method of demonstrating the presence of waves on parallel wires was devised by Professor Arons. The two parallel wires for the greater part of their length were inclosed in a glass tube from which the air could be pumped. When the proper degree of exhaustion is attained, and the wires in the tube are made to take the place of the parallel wires *WW* in air in Blondlot's apparatus (Fig. 45), a bright glow, as represented in Fig. 46, appears at intervals along the wires indicating the presence of a large fluctuation of potential (loop) at the positions of glow. This beautiful apparatus of Professor Arons exhibits to the observer at a glance the whole character of the potential distribution in the system.

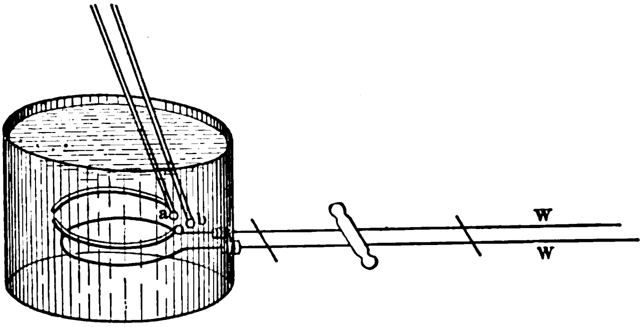

Fig. 45. Blondlot apparatus.

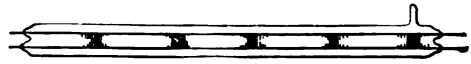

Fig. 46. Arons tube.

Exploration by the Bolometer. — In the place of the vacuum tube in experiments with waves on wires, Paalzow and Rubens[1] have shown how to adapt the bolometer to this purpose, and to obtain with it striking quantitative results.

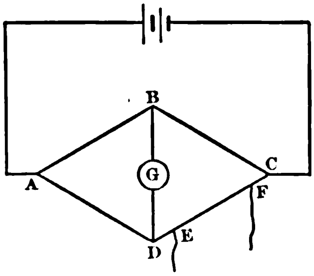

Fig. 47. Bolometer.

The bolometer (Fig. 47) consists of an accurately balanced Wheatstone bridge, so arranged that the oscillatory current to be measured is made to pass through a fine wire *EF* constituting one arm of the bridge. This oscillating current heats the fine wire, thereby changing its resistance, which throws the bridge out of balance and produces a deflection of the galvanometer *G*.

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[1] Paalzow and Rubens, Wied. Ann., Vol. 37, p. 529.

In Paalzow and Rubens's arrangement of apparatus (Fig. 48), in order to avoid disturbing the waves on the wires *PQRS*, the leads to the bolometer were not connected directly to the wires under examination, but were connected inductively by a single turn around capillary glass tubes *TT*, sliding on these wires. The glass tubes *TT* act as diminutive Leyden jars with the horizontal wires inside the tube for one coating, and the turn of wire on the outside of each tube for the other coating. Variations of electric potential at a point inside the little tubes induce (by electrostatic action) alternating potential in the turns of wire outside and produce alternating currents through one arm of the bolometer bridge.

Figure 48 shows a form of apparatus suitable for experiments with this method. This is the form of apparatus used by Professor St. John. As has been before mentioned, in order to get a simple stationary wave system in the parallel wires, these wires must have a proper length in comparison with the wave length of the waves. In St. John's experiment the proper length of the wires was determined by trial. The exploring terminals of the bolometer were put at the ends *P* and *S* of the wires of Fig. 48. The oscillator was set in activity, and a reading of the bolometer was taken for this length of wire. A few centimeters of wire were cut off, and the reading again taken. This process was repeated until a maximum point was passed. A sharp and unmistakable maximum was found when *PQ* had a certain length (859 centimeters). The effect fell off rapidly when the wires were shortened or lengthened from this point. The result is shown graphically in Fig. 49,

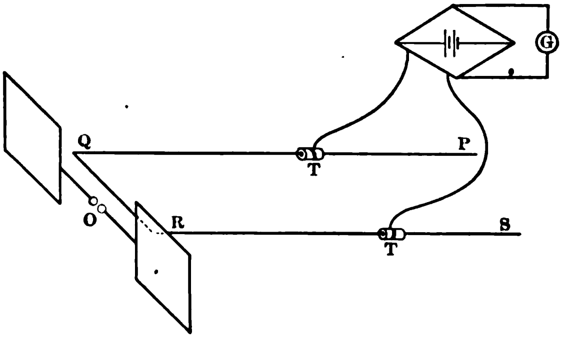

Fig. 48. Exploration of waves on wires by bolometer.

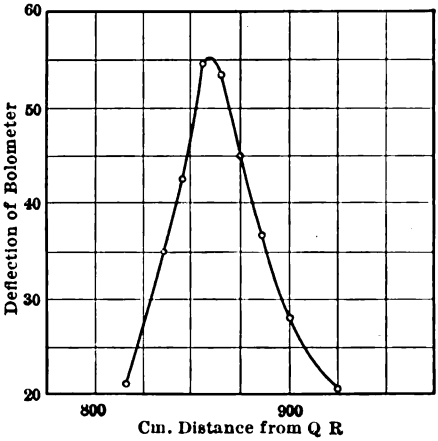

Fig. 49. Showing adjustment of parallel wires to resonance (Professor St. John).

where distances from Q are plotted horizontally, and deflections of the galvanometer are plotted vertically.

To determine the character of the vibration along the wire, the lengths of QP and RS were fixed at 859 centimeters, the exploring terminals were then moved along the wires, and the bolometer readings taken for each position of the exploring terminals. A diagrammatic representation of the result is shown in Fig. 50. The curve is seen to be simple in form, with maxima and minima at approximately equal intervals along the wires, and with a maximum at the ends of the wires.

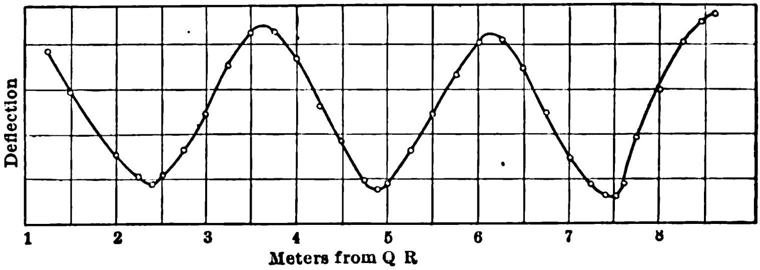

Fig. 50. Curve of distribution of potential on parallel wires (St. John).

The discussion of these experiments has been given at some length, because a wave system resembling that here described is produced in the antennæ used in wireless telegraphy, and the study of the resonance conditions in wireless telegraphy circuits will be seen to be closely related with the study of stationary waves in wires.

CHAPTER XI

WIRELESS TELEGRAPHY BEFORE HERTZ

By Conduction through Water. — The first successful attempt at electric telegraphy[1] between stations not connected by wires seems to have been made by S. F. B. Morse in 1842. Morse describes his experiments in a letter to the Secretary of the Treasury of the United States, which was laid before the House of Representatives on December 23, 1844. He says:

"In the Autumn of 1842, at the request of the American Institute, I undertook to give the public in New York a demonstration of the practicability of my telegraph, by connecting Governor's Island with Castle Garden, a distance of a mile; and for this purpose I laid my wires properly insulated beneath the water. I had scarcely begun to operate, and had received but two or three characters, when my intentions were frustrated by the accidental destruction of a part of my conductor by a vessel, which drew them up on her anchor, and cut them off. In the moments of mortification I immediately devised a plan for avoiding such an accident in the future, by so arranging my wires along the banks of the river as to cause the water itself to conduct the electricity across. The experiments, however, were deferred till I arrived in Washington; and on December 16, 1842, I tested my arrangement across the canal, and with success. The simple fact was then ascertained that electricity could be made to cross the river without other conductors than the water itself; but it was not until the last Autumn that I had the leisure to make a series of experiments to ascertain the law of its passage. The following diagram will serve to explain the experiment:

"*A*, *B*, *C*, *D* (Fig. 51) are the banks of the river; *N*, *P*, is the battery; *G* is the galvanometer; *ww*, are the wires along the banks connected with copper plates, *f*, *g*, *h*, *i*, which are placed in the water. When this arrangement is complete, the electricity, generated by the battery, passes from the positive pole *P*, to the plate *h*, across the

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[1] A large part of the historical information contained in this chapter was obtained from Mr. J. J. Fahie's excellent History of Wireless Telegraphy, Dodd, Mead & Co., 1902.

river through the water to the plate *i*, and thence around the coil of the galvanometer to plate *f*, across the river again to plate *g*, and thence to the other pole of the battery, *N*.

"The distance across the canal is 80 feet . . . . ."

In these experiments Morse found that it was necessary to make the wires along each shore three times as great as the distance from shore to shore across the stream.

Later, under Morse's direction, his assistants, Messrs. Vail and Rogers, established communication in the same way across the Susquehanna River, a distance of nearly a mile.

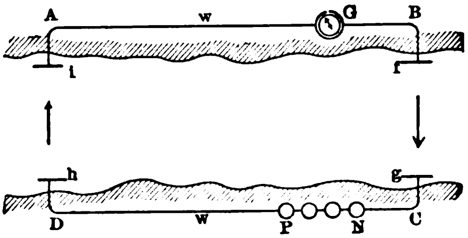

FIG. 51. Telegraphy by conduction through water (S. F. B. Morse).

Similar attempts to send signals through water by utilizing the water were made by James Bowman Lindsay between 1854 and 1860. By gradually increasing the power of his plant and the length of his conductors, Lindsay succeeded, with an apparatus like that of Morse, in signaling across the Tay where the river is more than a mile wide.

In 1880 Professor John Trowbridge of Harvard University suggested the use of circuits resembling those of Morse, modified by the employment of an interrupted current in the sending circuit and a telephone receiver in the receiving circuit. This modification takes advantage of the high sensitiveness, portability and rapidity of action of the telephone as a current indicator. About 1882 Professor Graham Bell made some successful experiments with the method suggested by Professor Trowbridge. The following is an extract from Professor Bell's description:

"Urged by Professor Trowbridge, I made some experiments which are of very great value and suggestiveness. The first was made on the Potomac River.

"I had two boats. In one boat we had a Leclanché battery of six elements and an interrupter for interrupting the current very rapidly. Over the bow of the boat we made water connection by a metallic plate, and behind the boat we trailed an insulated wire, with a float at the end carrying a metallic plate, so as to bring these two terminals about 100 feet apart. I then took another boat and sailed off. In this boat we had the same arrangement, but with a telephone in the circuit. In the first boat, which was moored, I kept a man making signals; and when my boat was near his I would hear those signals very well — a musical tone, something of this kind; tum, tum, tum. I then rowed my boat down the river, and at a distance of a mile and a quarter, which was the farthest distance I tried, I could still distinguish those signals."

In these experiments of Morse, Lindsay, Trowbridge and Bell the signals were carried from one station to the other by conduction through the water. The current in flowing from one submerged plate to the other at the sending station spreads out through the water in curves like those of Fig. 52. If, now, the terminals of the receiving circuit dip down into the conducting area, the current divides,—part going through the water and part through the receiving circuit, in the inverse ratio of their resistances. This method of signaling, though attempted with improved apparatus by Messrs. Rathenau, Rubens, and Strecker, and by the latter carried to a distance of 14 kilometers (8.7 miles), has not contributed to the art of wireless telegraphy, as it is now practiced.

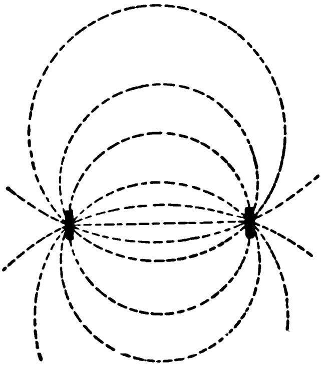

Fig. 52. Lines of flow.

Dolbear's Apparatus.—A somewhat more suggestive apparatus was invented by the late Professor Dolbear of Tufts College, Massachusetts, and was awarded a United States patent in March, 1882. Figure 53, taken from the patent specifications, shows a diagram of the apparatus. The transmitting station, shown at the left, consisted of a condenser H' connected to one terminal of the secondary of an induction coil G, of which the other terminal of the secondary was grounded at C. The primary of the induction coil contained a battery f' and microphone transmitter T. The receiving apparatus, shown at the right, consisted of a telephone receiver R with one terminal connected to ground at D, and the other terminal connected to a condenser H, which was in turn connected through a battery[1] B with a second condenser H^2.

Professor Dolbear, in his patent specifications, describes the action of the apparatus as follows:

" Now if words be spoken in proximity to transmitter T, the vibra-

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[1] The function of this battery is not evident.

tion of its diaphragm will disturb the electric condition of the coil *G*, and thereby vary the potential of the ground at *A*, and the variations of the potential at *A* will cause corresponding variations of the potential of the ground at *B*, and the receiver *R* will reproduce the words spoken in proximity to the transmitter, as if the wires *CD* were in contact, or connected by a third wire. Electrical communications may be thus established between points certainly more than half a mile apart; but how much farther I cannot now say."

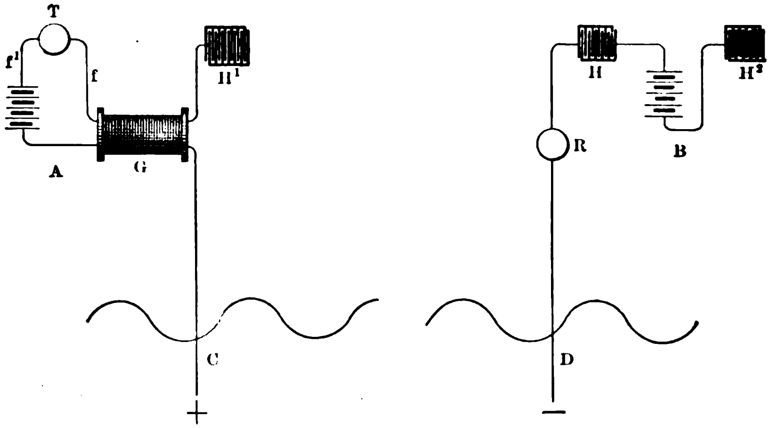

FIG. 53. Dolbear's apparatus for wireless telegraphy.

In some other of Professor Dolbear's writings he speaks of using an automatic break and a Morse key in the primary of his coil instead of the microphone transmitter, and he also speaks of using a gilt kite carrying a fine wire from the secondary of the Ruhmkorff coil.

Professor Dolbear thus made an approach to the method that was subsequently, in the hands of Marconi, to be crowned with success. The difficulty with the Dolbear apparatus was that the elevated conductor had to discharge through the secondary of the induction coil, and thus (as we see now) had a very low frequency, so that the inductive action of the waves emitted was very feeble. Dolbear, therefore, did not have in his sending station the one essential that makes the Marconi sender a success; namely, *electrical oscillations of high frequency.* Also the detector used in Professor Dolbear's apparatus (his electrostatic telephone receiver) was not of sufficient sensitiveness.

Sir William Preece's Method. — Another serious attack on the problem of wireless telegraphy, before the work of Hertz and

Marconi had made the way clear, was made by Sir William Preece, engineer-in-chief of the postal telegraph system of England. Preece attempted to utilize the electromagnetic induction between two long horizontal wires, one at the sending station and the other at the receiving station. These horizontal wires were supported parallel to each other on telegraph poles, and were grounded at their two ends. The sending wire contained a battery and an interrupter, or else an alternating current generator, so that the line was traversed by an interrupted or an alternating current; while the receiving circuit contained an ordinary telephone receiver. The surging current in the sending wire produced a variable magnetic field surrounding it. This variable magnetic field produced by the sending circuit cut or linked with the receiving circuit, and induced a periodic electromotive force in it, which was evidenced by sounds in the receiver.

After several years of experimenting, Sir William Preece was able to utilize this apparatus for signaling to some of the islands a short distance off the coast of England, and in 1898 a regular installation was established at Lavernock Point on the mainland and at Flatholm in the Bristol Channel, 3.3 miles (5.2 kilometers) apart.

Preece's experiments can be said to have availed only to show the futility of the attempt to get inductive action at long distance without the use of *oscillations of high frequency.*

CHAPTER XII

WIRELESS TELEGRAPHY BY HERTZIAN WAVES.
MARCONI, 1896–1898

We come now to the application to wireless telegraphy of the principles discovered by Maxwell and Hertz. For this application we are chiefly indebted to the genius, skill, and forceful initiative of Signor Guglielmo Marconi. We are to see, however, that the achievement did not come as a scientific revolution, but as a steady development to which many other investigators also contributed.

The Coherer. — In the extension of the effects of the Hertzian waves to great distances the first need was a detector of high sensitiveness. Such a detector was already at hand in a crude form; for as long ago as 1866 S. A. Varley had discovered that metallic filings in a loose condition have a high resistance and that this resistance is decreased to a small value under the action of an electric discharge sent through the filings. This fact was utilized by Varley in the construction of a "lightning bridge," or lightning arrester, used to protect electrical apparatus from lightning. Varley had also noticed that the resistance of the filings, when lowered by the discharge, could be brought back to its high value by tapping or shaking the vessel containing them.

In 1884 Calzecchi-Onesti also made and published some independent experiments on this interesting phenomenon, verifying and extending the results of Varley.

This work of Varley and Onesti remained unnoticed until 1890, when Professor E. Branly, of the Catholic University of Paris, rediscovered the phenomenon. Professor Branly studied the conductivity of metallic filings placed in a glass tube between two metallic plugs, by which the filings could be put into an electric circuit. He found that the filings were rendered conductive by electric discharges in the neighborhood of the tube, even when the discharges did not actually pass through it. He also observed that tapping the tube restored the filings to their high resistance. He gave the name "radio-conductor" to the apparatus, and made many interesting experiments in the effort to obtain an explanation of its action. Branly's radioconductor is now familiarly known as the "coherer," — a name invented by Sir Oliver Lodge.

Coherer Applied to Study of Electric Waves. — In 1893 and 1894 Sir Oliver Lodge applied the coherer to the study of electric waves by putting it in the place of the micrometer spark gap in a Hertz resonator, as is shown in Fig. 54. Under the action of the electric waves sent out from a properly placed Hertz oscillator, the resistance of the metallic filings in the coherer fell to a low value, so that the galvanometer G connected in series with a battery B in a local circuit through the coherer gave a deflection. After the waves ceased the resistance of the coherer remained low, so that the galvanometer remained deflected. In order to prepare for another reading it was necessary to restore the filings to high resistance by tapping the tube. Lodge effected this restoration either by a tapping mechanism driven by clockwork, or by an electric trembler (like an electric bell) mounted on the same base as the coherer.

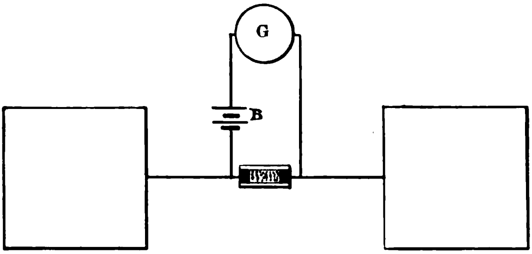

FIG. 54. Sir Oliver Lodge's apparatus for detecting electric waves.

With this apparatus Professor Lodge succeeded in detecting Hertz waves at a distance of about 55 yards from the source.

Experiments of Popoff. — A still nearer approach to an operable form of receiving apparatus for wireless telegraphy was made in 1895 by Professor Popoff of Kronstadt, and a description of the apparatus was communicated by him to the Physico-Chemical Society of St. Petersburg in April of that year. Popoff's apparatus, which was designed for use in the study of atmospheric electricity, is shown in the diagram of Fig. 55. The left-hand terminal of the coherer was connected to a metallic rod extending above the house-top; the right-hand terminal of the coherer was connected to earth; so that electric currents produced by the atmospheric electricity were conducted to earth through the coherer. Through the coherer there was also a local circuit containing a battery *B* and a relay *R*. Under the action of the atmospheric electrical disturbances, the filings in the coherer became conductive, so that a current from the battery flowed through the coherer and around the electromagnet of the relay. This current magnetized the core of the relay and attracted the armature so as to close the contact at *D*, which put the battery in circuit with an electric bell. The bell was so placed that its hammer while in vibration struck the bell, and also struck the coherer, causing it to decohere. Thus the atmospheric discharges caused the bell to sound, and after the cessation of the discharge the filings were decohered so that the bell ceased to sound and awaited another discharge.

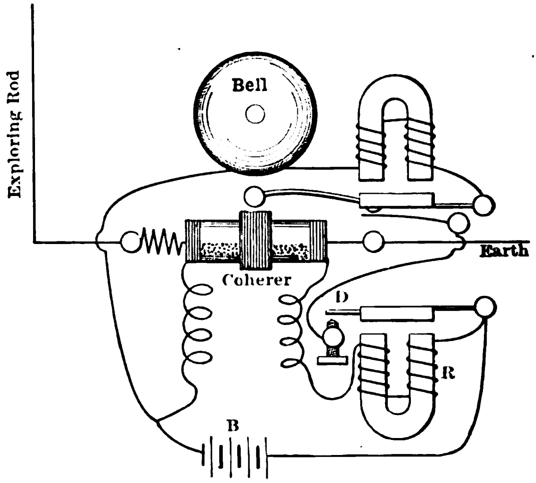

FIG. 55. Professor Popoff's apparatus for studying atmospheric electricity.

In addition to the bell, Popoff used also a telegraphic registering apparatus in shunt with the bell, so as to get a written record of the duration of each atmospheric electric disturbance.

In a note, dated December, 1895, he says: "I entertain the hope that when my apparatus is perfected it will be applicable to the transmission of signals to a distance by means of rapid electric vibrations — when in fact a sufficiently powerful generator of these vibrations is discovered." [1]

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[1] This quotation is from Fahie's History of Wireless Telegraphy, 1902.

Marconi's 1896 Apparatus. — We come now to the early work of Marconi. After having made some preliminary experiments on his father's estate near Bologna in Italy, Signor Marconi went to England, and on June 2, 1896, filed in the Patent Office of Great Britain a part of his first application for a patent for "improvements in transmitting electrical impulses and signals, and in apparatus therefor." The part of the application filed at this date is without diagrams, and contains only *provisional specifications*. A *complete specification* covering the same subject matter, amply illustrated with drawings and full of details as to the invention, was filed March 2, 1897. This patent application of Mr. Marconi contains the first published account of a completed apparatus for successful wireless telegraphy by electric waves, and is, therefore, a document of considerable interest. It would seem to be not unprofitable to give careful attention to Marconi's description of his invention.

In the description that follows, the quotations are taken from the Marconi patent specifications; and after some of the paragraphs of quoted or paraphrased description I have added a brief paragraph in the form of a summary.

Hertz or Righi Oscillator and Receiver. — At the transmitting station he employs " a Ruhmkorff coil having in its primary circuit a Morse key for starting or interrupting the current." The secondary of the coil he connects to " pole appliances " for producing the desired oscillations. Under " pole appliances " he mentions " insulated balls separated by small air spaces or high vacuum spaces, or compressed air or gas, or insulating liquids kept in place by a suitable insulating material, or tubes separated by similar spaces and carrying sliding discs."

This form of the transmitting apparatus, as may also be seen by reference to the original drawings, is an ordinary Hertz or Righi Oscillator, actuated by a Ruhmkorff coil with a Morse key in its primary circuit. There is, however, also the suggestion of the use of a high vacuum or compressed air or gas about the spark gap.

" At the receiving instrument there is a local battery circuit containing an ordinary receiving telegraphic or signaling instrument and an appliance for closing the circuit." The appliance for closing the circuit " consists of a tube containing conductive powder, or grains, or conductors in imperfect contact, each end of the column of powder or the terminals of the imperfect contact or conductor being connected to a metallic plate of suitable length so as to cause the system to resonate electrically in unison with the electrical oscillations transmitted to it."

This part of the apparatus is, therefore, essentially the receiving apparatus of Lodge shown in Fig. 54, with a telegraphic relay or sounder substituted for the galvanometer *G*. That the substitution could be made had already been shown in detail by Popoff.

The specifications say further: "When transmitting through the air, and it is desired that the signal or electrical action should only be sent in one direction, or when it is necessary to transmit electrical effects to the greatest possible distance without wires, I place the oscillation producer at the focus or focal line of a reflector directed to the receiving station, and I place the tube or imperfect contact at the receiving instrument in a similar reflector directed towards the transmitting instrument."

This part of the specification provides for the use of reflectors like those of Hertz. However, on account of the difficulty of constructing reflectors sufficiently large, the reflectors were soon abandoned by Marconi in his practical work, and have not been subsequently revived.

Grounded Circuits. — He says further: "When transmitting through the earth or water I connect one end of the tube or contact to earth and the other end to conductors or plates, preferably similar to each other, in the air and insulated from the earth." A diagram of this receiving apparatus is shown in Fig. 57. The corresponding earthed sending apparatus is shown in Fig. 56.

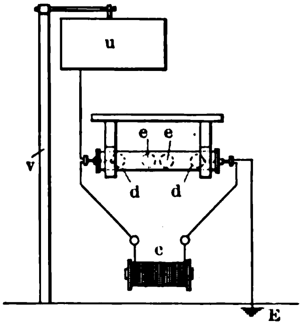

Fig. 56. Mr. Marconi's 1896 transmitter.

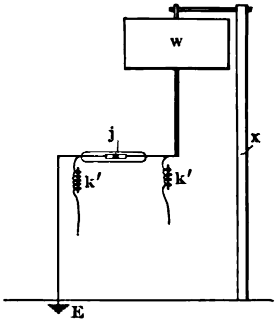

Fig. 57. Marconi's 1896 receiver.

The earthing of the circuits was for a time considered to be the strongest feature of the Marconi apparatus; but recent experiments have shown that the earthing of the circuits, though a convenience in construction, is not essential.[1]

It was with these earthed circuits that Marconi made his first great gains in the distance of transmission; but as we now look back over the experiments, we see that the gain in distance came about primarily through the fact that with this apparatus his circuits were placed vertical rather than horizontal, and also through the use of longer waves and more energy and larger radiating and receiving antennæ, rather than through the use of the mere earth connections. To this subject we return in Chapter XIV.

Marconi's Coherer. — In addition to the practical introduction of the vertically placed radiator with ground connection Signor Marconi also made tremendous progress over other early investigators in his skill in constructing and using the coherer. A sketch of the coherer, drawn natural size from Marconi's specifications, is shown in Fig. 58. The metal plugs *PP* are of silver slightly amalgamated with mercury, but no excess of mercury in the form of globules is left on them. The plugs fit accurately into a glass tube, and are within $\frac{1}{30}$ inch of each other. The filings in the space between the plugs are preferably 96% nickel and 4% silver, and should not be fine, but rather coarse. They should be dry and free from grease and dirt, and should be uniform in size. The tube containing the filings is preferably exhausted of air and sealed up. In sealing up the tube care should be taken not to oxidize the filings. In order that the coherer may not be injured by the current through it, not more than $\frac{1}{1000}$ of an ampere of current should be used in the local circuit.

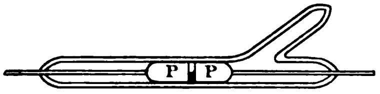

FIG. 58. Marconi coherer (natural size).

Marconi's Decohering Device.—One of the greatest difficulties to be overcome in operating a delicate coherer arises from the fact that the signal causes the coherer to become conductive, and if left alone, the coherer perseveres in this conductive condition. In order to restore it to its high resistance so as to be ready for the next signal, it is necessary to employ an automatic tapper, or trembler, which is started into action by the incoming impulse, and which stops the signal and itself when the incoming impulse ceases. Signor Marconi brought the decohering device to a high state of perfection, and as a result changed the capricious tube of filings into a reliable instrument for practical use.

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[1] See Chapter XIV.

A diagram drawn from Marconi's descriptions is shown in Fig. 59. The continuous lines of the drawing show the coherer *Co*, the relay *R*, the trembler *T*, and the sounder *S*, and their circuits. These had been used in almost the same form by Popoff. The dotted lines *p*, p_1, *q*, *q'*, and *h* show the further improvements, introduced by Marconi, and consisting of resistances to prevent the inductive kick of the instruments from acting on the coherer. The action of the decohering device and the protective resistances

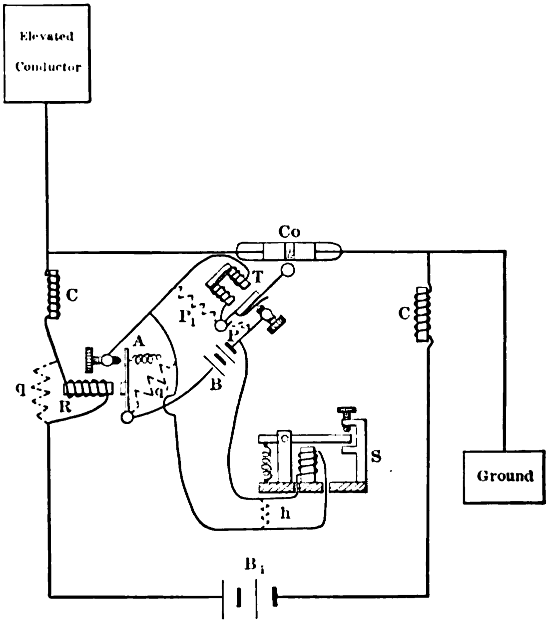

Fig. 59. Receiving circuit showing coherer and protective devices.

may be best understood by following the process as an actual message is sent from one station and received by another. This is done in the next paragraph.

Action of the Apparatus in Sending and Receiving. — Let us suppose the Morse key in the primary of the Ruhmkorff coil at the sending station to be operated as in ordinary line telegraphy. While the key is closed, the interrupter in the primary of the coil makes and breaks the circuit at the rate of, say, 100 a second. At each break of the primary the potential of the secondary rises to a high value and charges the oscillator sufficiently to produce a spark. We have thus in our supposed case 100 sparks a second. Each spark occurs with oscillations of very high frequency and produces a train of electric waves. With such a sending station we should have arriving at the receiving station a train consisting of a few [1] of these extremely rapid waves, followed $\frac{1}{100}$ of a second later by a second similar train; and thus at intervals of $\frac{1}{100}$ second there would arrive successive short trains of waves while the sending key is depressed.

Under the action of these trains of incoming waves the filings in the tube cohere, so that a current flows from the battery B_1 (Fig. 59) through the coherer *Co* and the relay *R*. This battery current pulls the armature of the relay so as to close the gap at *A*. When the gap is closed a second battery *B* sends a current through the coils of the sounder *S*, and also through the coils of the trembler *T*. The trembler is like an electric bell (with a somewhat shorter striking arm), and makes a series of strokes against the tube of the coherer. This decoheres the filings, but so long as the key at the sending station is closed, the waves continue to arrive and cause a repetition of the coherence, thus putting the coherer in a state of repeated coherence and decoherence during the arrival of the waves. The armature of the relay is adjusted so that the relay is somewhat sluggish and does not open at each decoherence. Therefore, the contact of the relay remains closed, and consequently the sounder armature stays down as long as the trains of waves continue to arrive. When, however, the sending key is released, and the waves cease to arrive, the decoherence due to the tapper perseveres, the relay contact opens, the sounder arm is released, and at the same time the trembler stops. Thus each closing and opening of the key at the sending station produces a corresponding down and up stroke of the sounder, making a dash or a dot, according as the sending key is depressed for a long or a short interval of time.

Instead of the sounder for translating the message an ordinary Morse registering tape-machine may be used to give a written record of the dashes and dots.

Marconi's Protective Resistances and Inductances. — Returning now to diagram Fig. 59, let us examine into the purpose of the resistances p, p_1, q, q', and h, represented by the dotted lines.

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[1] I have taken revolving-mirror photographs of the spark of a Marconi Oscillator with a period of $\frac{1}{1000000}$ second, and found that there are about 12 waves in a train.

One of these resistances is shunted about each of the electromagnets of the circuit and one about each make-and-break contact in the circuit. These resistances are for the purpose of preventing a sudden rise of electromotive force in any of the circuits due to the action of the self-inductances of the electromagnet. We have learned in Chapter III that when a current is flowing in a large self-inductance, — for example, through the coherer and relay, — and the circuit is suddenly interrupted, — e.g., by a stroke of the tapper against the coherer, — the self-inductance in the circuit produces a large electromotive force tending to cause the current to continue. This large e.m.f. of inductance in the coherer circuit is equivalent to a discharge through the coherer, and if not prevented would affect the coherer and cause it to cohere again, when in fact the tapping was designed to cause it to decohere. This action is prevented by the resistance q shunted about the relay. In a similar manner the other resistances absorb the energy sent into the circuit by the inductive kicks from the other electromagnets, which would otherwise act either directly or inductively on the coherer.

Mr. Marconi gives the following appropriate values for these resistances: p and p_1 ought each to be of resistance four times the resistance of the trembler; the resistance of q should be three or four times that of the relay; q' should be about 20,000 ohms, or should be a water resistance offering polarization voltage equal to the battery B_1; h should have a resistance equal to four times the resistance of the telegraph instrument S. These resistances should all be non-inductive. The resistance of the relay itself should be more than 1000 ohms, and the working current should be less than $\frac{1}{1000}$ ampere.

Two coils of a few turns of wire CC wound inductively on iron cores are inserted in the relay circuit to prevent the electric oscillations due to the incoming waves from escaping the coherer by going into the relay circuit. However, the inductance of the relay itself effects this purpose to a large extent.

The decohering and protective devices described in Marconi's patent specifications are still a model for the proper construction of these important accessories to the coherer. Recently, however, the coherer has been almost completely replaced by other forms of detectors operating on other principles and that do not need to be decohered. These newer detectors are the subject matter of a later chapter.

Balloons or Kites. — Another important suggestion contained in the 1897 specifications is the suggestion that "the larger the plates of the receiver and the transmitter, and the higher from the earth the plates are suspended, the greater is the distance at which it is possible to communicate at parity with other conditions." "Balloons can also be used instead of plates on poles, provided they carry up a plate or are themselves made conductive by being covered with tinfoil. As the height to which they may be sent is great, the distance at which communication is possible becomes greatly multiplied. Kites may also be successfully employed if made conductive by means of tinfoil." This sentence, therefore, provides for the use of antennæ of great height. It should be noted here that the plates or tinfoil covering on the balloons or kites, which the inventor makes a necessary provision of the apparatus, are really nonessential.

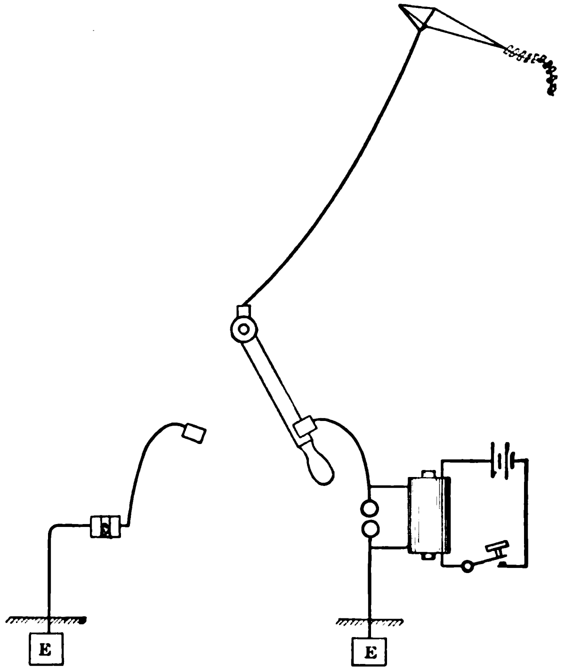

Fig. 60. Simple Marconi circuits with antenna sustained by a kite. Switch for "cutting over" from sending to receiving.

A diagram of circuits in which kites are used for suspending the vertical wires is shown in Fig. 60.

Shifting from Sending to Receiving.— In practice there are both a sending and a receiving apparatus at each station. Only one antenna is needed, and this is shifted from the spark balls to the coherer, in changing from sending to receiving. This shifting is done by means of a switch, as is shown in Fig. 60, or by means of the key itself, as is shown in Fig. 61. In Fig. 61 the key, which is also a switch, is in the position for sending, and the coherer, which is at *R*, is disconnected from the antenna. When the message is finished, or, if desired, between words of the message, the key is released, and the arm *b*, which is insulated from b^1, is allowed to descend so that the contact point b^2 rests on the point b^3. This connects the antenna with the coherer and puts the station in a condition to receive.

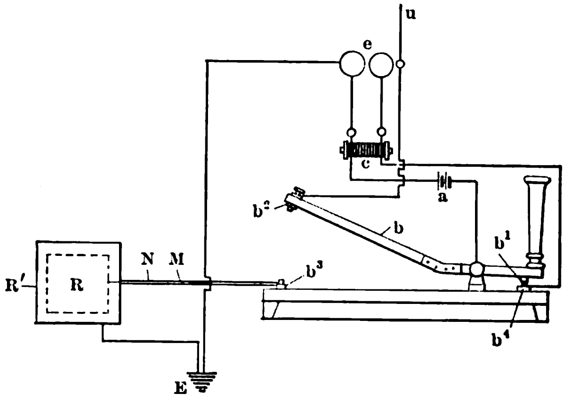

Fig. 61. Marconi's key for changing from sending to receiving.

The "Claims" of Marconi's 1896 Patent. — The "claims" of a patent are a series of succinct statements at the end of the descriptive matter and are supposed to embody the invention in its most general form. Signor Marconi's English patent of 1896 contains nineteen claims. The three most comprehensive of these claims are the following:

15. A receiver consisting of a sensitive tube or other imperfect contact inserted in a circuit, one end of the sensitive tube or other imperfect contact being put to earth whilst the other end is connected to an insulated conductor.

16. The combination of a transmitter having one end of its sparking appliance or poles connected to earth, and the other to an insulated conductor, with a receiver as is mentioned in claim 15.

17. A receiver consisting of a sensitive tube or other imperfect contact inserted in a circuit, and earth connections to each end of the sensitive contact or tube through condensers or their equivalent.

Marconi's Achievements between 1896 and 1898. — In July, 1896, soon after arriving in England, Mr. Marconi submitted his plans to Sir William Preece, director of the postal-telegraph system of England. Preece, of whose activity in connection with attempts at wireless telegraphy we have already learned, entered eagerly into the new experiments.

The first messages were sent from a room in the General Post Office to an impromptu station 100 yards distant. Soon afterwards, at Salisbury Plain, with parabolic reflectors about the instruments, communication was established at a distance of two miles. In May, 1897, discarding the reflectors and using grounded circuits, Mr. Marconi covered a distance of 8.7 miles between Lavernock Point and Brean Down. Kites were employed in this experiment to support the vertical wires.

In July, 1897, important trials were made at Spezia, Italy, at the request of the Italian Government, and communication was established at a distance of 12 miles between a warship and a shore station.

In July, 1898, the Marconi apparatus was used to report the yacht races at the Kingston Regatta, and a large number of correct messages were exchanged between a press boat and the shore at distances extending up to 20 miles.

These various experiments constituted a complete demonstration of the utility of the invention.

CHAPTER XIII

ELECTRIC WAVE TELEGRAPHY BY RESONANT CIRCUITS

A SIMPLE radiating circuit,[1] like that shown in Fig. 60 of the preceding chapter, consisting of a spark gap with one side grounded and the other attached to an antenna, has a definite period of electric oscillation. The receiving circuit has also a characteristic period of oscillation. A maximum effect will be obtained when the two have the same fundamental period; that is to say, when the two circuits are in resonance. Marconi recognized this fact, and in his specifications, particularly with reference to the use of a receiving resonator of two metallic vanes, he provides a method of experimentally determining the size of the vanes that will give resonance with the transmitter.

In the course of further experiments it was soon found, however, that the type of simple receiving conductor in which the coherer is inserted directly in the antenna circuit is not a very discriminating resonator. Also it is usually not practicable to change the size of the vanes or the length of the vertical wires in order to make changes in the period of the circuit.

When several wireless telegraph stations are to be operated at once, it is highly desirable, in order to be able to avoid confusion, to have a method of readily adjusting the receiving circuit to resonance with the wave lengths it is desired to receive and out of resonance with undesired signals of a different wave length. Several methods have been devised for accomplishing this result, which though attaining only limited success, have yet been of great advantage in wireless telegraphy. Circuits capable of being attuned, or adjusted for resonance, are called *syntonic circuits*, or *resonant circuits*.

In the present chapter it is proposed to discuss some of the general types of resonant circuits. Quantitative experiments in regard to resonance, and some of the practical details of construction of apparatus, will be given later.

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[1] We shall refer to a rectilinear oscillator of this character as a *circuit*, since according to the work of Maxwell a circuit need not be conductively closed.

A Simple Variable Circuit. — A simple method of easily varying the period of a receiving circuit consists in the use of a variable inductance *L* (Fig. 62), inserted between the detector and the antenna or between the detector and the ground at the receiving station. Such a variable inductance, or tuning coil, is made of a single layer of wire wound on an insulating tube of glass or ebonite, and is varied by a contact sliding along the coil so as to put more or fewer turns of inductance into the circuit. A similar tuning coil, though usually of larger wire, may be used at the sending station also. At the sending station the coil is inserted between the spark gap and the antenna or between the spark gap and the ground connection.

Increase of inductance in either circuit increases the time of vibrations, which brings a corresponding increase of wave length.

The use of adjustable inductances in both the sending and the receiving circuits was apparently first suggested by Sir Oliver Lodge in a patent application of 1887, which is reviewed later in the present chapter.

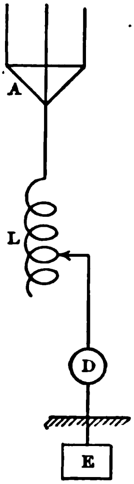

FIG. 62. Simple antenna circuit having a variable inductance for tuning.

Coupled Circuits. — Certain other methods, employed for adjusting both the sending station and the receiving station, and found to produce better results both for transmitting with large quantities of energy and for receiving with comparatively sharp resonance, make use of *coupled circuits*. The resonance relations in these coupled circuits has been the subject of much theoretical and experimental research. As introductory to the description of the coupled circuits, I shall recall to the reader the familiar and interesting experiments of Mr. Tesla and of Professor Thomson on the production of electric oscillations of high frequency and high potential.

High-frequency Transformers of Thomson and Tesla. — The high-frequency transformer that was apparently independently developed by Mr. Nikola Tesla and Professor Elihu Thomson about 1890 is shown in sketch in Fig. 63. A primary coil *P*, consisting of one or two turns of heavy wire, is connected in series with a bank of Leyden jars *C* and a spark gap *G*. A secondary coil *S*, consisting of three or four hundred turns of wire wound in a single layer on a paper or vulcanite tube, is inserted axially within the primary. When the bank of jars is connected by means of the leads *W*, *W′* with the secondary of a Ruhmkorff coil, or better with the secondary of an alternating current step-up transformer, the Leyden jars are repeatedly charged by the Ruhmkorff coil or transformer at intervals of, say, $\frac{1}{100}$ or $\frac{1}{200}$ of a second. When the potential at each charge of the jars reaches a value high enough to spark across the gap *G*, the jars discharge with oscillations of extremely high frequency. A group of these oscillations occurs during each spark at the gap *G*. These high-frequency oscillations in the primary coil *P* act inductively on the secondary coil *S*, and on account of the extreme rapidity of change of current in the primary, the electromotive force induced in the secondary is very high, and produces a series of sparks between the terminals T_1 and T_2 of the secondary.

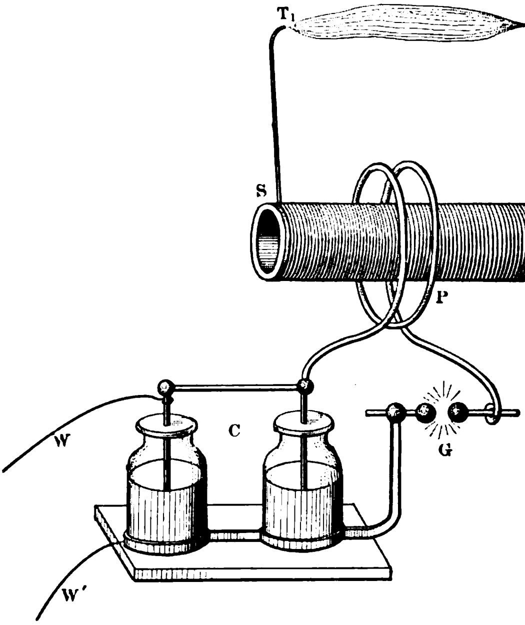

Fig. 63. Tesla or Thomson coil.

It should be noted that the primary has a period of its own, and that the coil of wire *S* used as a secondary has also a period of its own; and in order to get the greatest spark at the secondary terminals, it is necessary to adjust the number of jars *C* or else the number of turns of wire on either *P* or *S*, so that the condenser circuit and the secondary coil shall be in resonance with each other.

By the use of apparatus of this character Mr. Tesla has produced enormous sparks — twenty-three feet long and of great volume — graphically described as being accompanied by a roar like Niagara.

The transformer *PS* is called *a high-frequency transformer*, *an oscillation transformer*, or *an air-core transformer*, to distinguish it from an ordinary iron-core transformer, such as is used with commercial alternating currents of slow frequency.

Oscillation transformers, built on somewhat different lines from the one above described, have met with application to both the sending and the receiving circuits of electric-wave telegraphy, and by the use of these transformers a considerable advance has been made, both in the greater distances attained and in the diminished confusion of signals of different wave lengths.

Two Systems of Coupled Circuits. — The form given to these coupled circuits is considerably varied in practice. There are, however, two important general types. These are represented in the accompanying figures (Fig. 64 and 65) and are called respectively the *inductively coupled* and the *direct coupled* types.

The Inductively Coupled Type. — This type is shown in Fig. 64. In this system the sending station, shown on the left, is seen to consist of a Tesla high-frequency apparatus, with one secondary terminal connected to an antenna and the other secondary terminal connected to the ground. Power is supplied to the circuit by an alternating current transformer or a Ruhmkorff coil to which the wires *W*, *W′* lead.

The receiving station of this system, shown at the right in Fig. 64, has also an oscillation transformer *P′ S′*, and is in principle like the sending station, except that the detector *D′* with its accessories is usually put in place of the spark gap of the sending apparatus. The coils *P′* and *S′* and condenser *C′* used with the receiving apparatus generally have different inductances and capacity from those of the sending apparatus, and not being traversed by high-potential currents they are usually made more compact.

In this inductively coupled system of circuits, oscillatory currents in the sending antenna are produced inductively by the oscillatory discharge of the condenser *C* through the primary coil *P*. These oscillatory currents in the sending antenna produce electric waves, which travel away in all directions with the velocity of light (186,000 miles per second). Arriving at the receiving station these electric waves set up oscillations in the antenna circuit $A'P'E'$. These currents through P' act inductively on S', and produce oscillatory currents in the detector circuit.

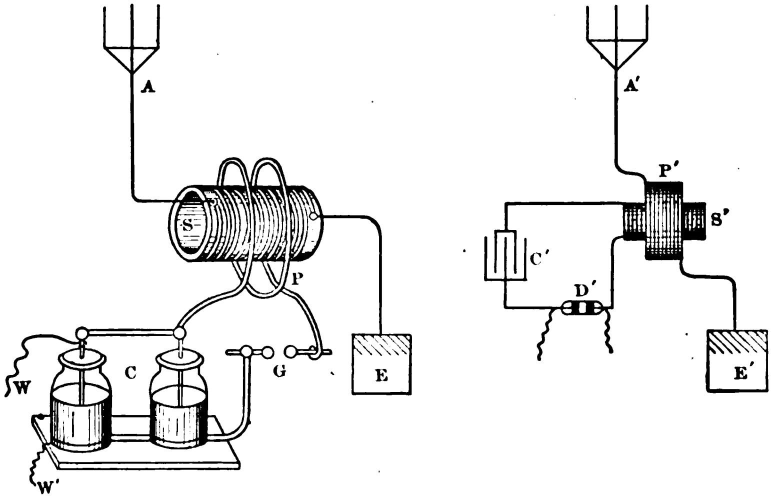

FIG. 64. Inductively coupled transmitting and receiving circuits.

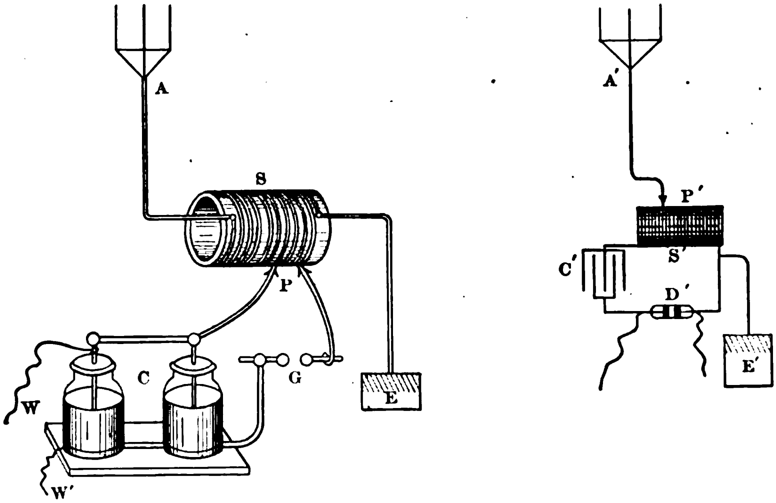

FIG. 65. Direct coupled transmitting and receiving circuits.

The Direct Coupled Type.—Figure 65 shows the other form of coupled apparatus, constituting the *direct coupled system.* This system employs auto-transformers; that is to say, instead of having separate primary and secondary coils in the high-frequency transformer, the primary coil (*P* or *P′*) at either station is a part of the secondary coil. At the sending station (at the left) the condenser discharges through some of the turns of the secondary, and the discharge acts inductively on the whole of the secondary. Likewise, at the receiving station the oscillations in the antenna pass through a part *P′* of the secondary *S′* and act inductively on the whole of *S′*. Theory and experiment show that in principle the direct coupled circuits differ very little from the inductively coupled system.

Introduction of Coupled Circuits into Practice. — Postponing for a time the direct discussion of the principles involved in the use of the coupled circuits, let us take up historically the matter of the introduction of these circuits into wireless telegraph practice. The examination of the question as to the priority of the different claimants to this improvement is fraught with considerable difficulty. Lodge, and Marconi in England, and Braun in Germany, have clearly established dates of publication by patent applications. While examining the question of priority, I shall also give a brief description of the apparatus of these several inventors, so far as pertains to the form of circuits used.

Sir Oliver Lodge's Apparatus. — On May 10, 1897, Professor Lodge filed a patent application in England for improvements in wireless telegraphy. The corresponding application in the United States was filed Feb. 1, 1898. What he claims to be the most promi-

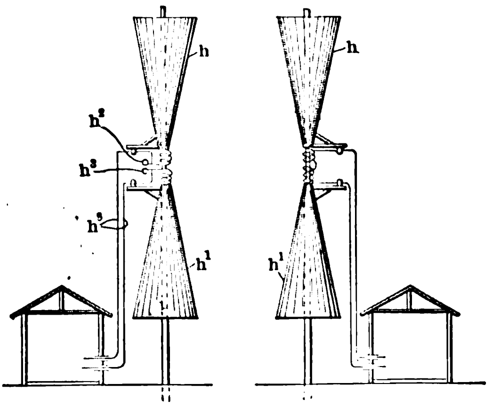

Fig. 66. Lodge's transmitter and receiver.

nent feature of his invention is represented in Fig. 66. The emitter and receiver consist preferably of two large conical conductors, called *capacity areas*, supported by poles; but horizontally placed conductors may also serve as his capacity areas, and one of these capacity areas, he says, may be the earth.

At the sending station (left) he joins the two capacity areas h and h^1 to polished knobs h^2 and h^3. Between either capacity area and its knob he places a syntonizing self-inductance coil. " The object of this coil," Lodge says, is " to prolong the electric oscillations occurring in the radiator, so as to constitute it a radiator of definite frequency or pitch and obtain a succession of tone waves emitted, and thereby to render syntony in a receiver possible, because exactitude of response depends on the fact that the total number of oscillations in a suitably arranged circuit is very great." He provides also for varying the number of active turns of these coils for the purpose of varying the period of the circuits.

After having described the ordinary way of charging the vanes of the emitter by connecting them directly or through small spark gaps to the secondary of a Ruhmkorff coil, as Hertz and Righi had

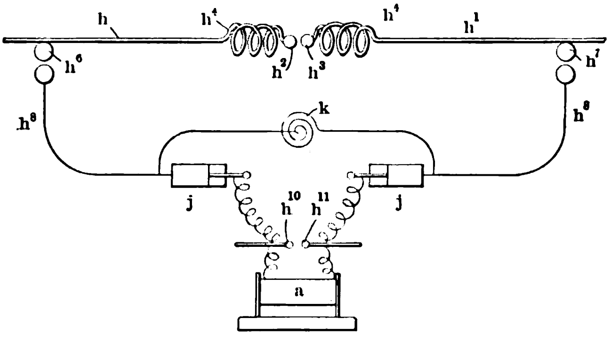

FIG. 67. Lodge's apparatus for exciting an antenna by means of a Leyden jar discharge.

done, Lodge proposes also the use of Leyden jars in the manner shown in Fig. 67. In this diagram the jars are shown at *jj*. The inner coatings of the jars are connected to the secondary of a Ruhmkorff coil, the outer coatings of the jars are joined by an inductance coil of thin wire *k*. This coil is necessary in order that the jars may charge. When the jars discharge across the gap $h^{10}h^{11}$, sparks also appear across the gaps h^6h^7 and h^2h^3. This apparatus, therefore, shows the use of a Leyden jar circuit discharging into the antenna circuit, and if the coil *k* has a large inductance, as it seems to have from the fact that it is made of " fairly thin wire," this sending arrangement may be looked upon as a special and very imperfect form of the direct-coupled type of sending circuit of Fig. 65. It is imperfect in the use of the multiplicity of spark gaps, for if all the gaps except $h^{10}h^{11}$ had been closed, the coil *k*, which was put in as a charging bridge across the unnecessary gaps, could then have been omitted, and the apparatus would have been a very useful form of direct-coupled emitter.

While we are accustomed to the use of multiple gaps in replacement of a single gap, and while the multiple gap is in some constructions a distinct advantage over the single gap, still the introduction of one of the multiplicity of gaps directly into the antenna circuit is certainly an annulment of the chief advantage accruing from the coupled circuits.

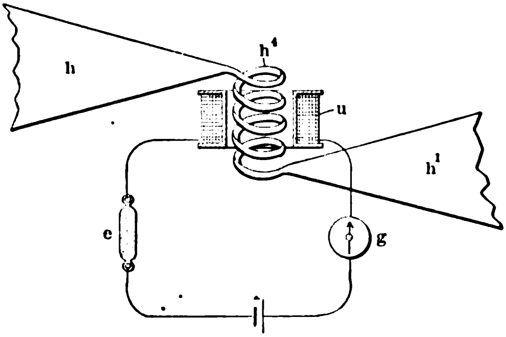

FIG. 68. Lodge's inductively coupled receiving transformer.

In the receiving apparatus Lodge shows the use of an oscillation transformer. Reference is made to Fig. 68. His conical capacity areas or their equivalent are connected to the primary coil h^4. About this a secondary coil *u* is placed, and is connected with the coherer *e*, a battery *f*, and the telegraphic receiving instrument *g*. The purpose of connecting the detector in a secondary circuit instead of directly in the antenna, is, according to the patentee, to " leave the resonator freer to vibrate electrically without disturbance from attached wires." This is an excellent reason, but the receiving apparatus, as shown in this diagram, which was taken from Lodge's patent specifications, has the fatal defect that no condenser is shown in the secondary circuit, and that the high-frequency oscillations have to go through the telegraph instrument. Hence, apart from the suggestion of the use of a transformer in the receiving apparatus, we cannot consider this circuit of Lodge to be a clear disclosure of the inductively coupled receiving system.

Later Lodge and Muirhead, in a British specification filed Dec. 8, 1897, partially remedied the above defect, by the arrangement of circuits shown in Fig. 69. Between the two winged-shaped capacity areas *AA*, they inserted an inductance coil *d*, and a large condenser *C*. About this condenser a battery *B* and a telegraph instrument *I* are connected; and about both inductance and condenser is connected a coherer *Co.* With proper values of the inductance and capacity, this arrangement is a special case of the direct coupled receiving apparatus.

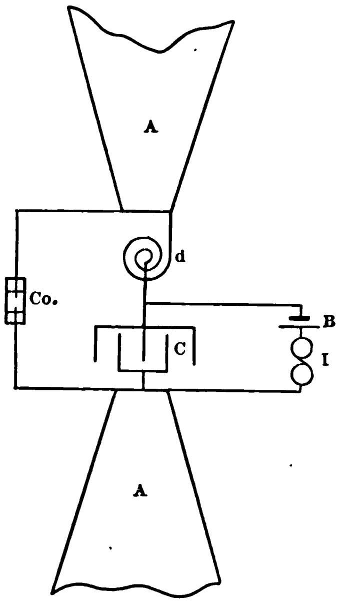

FIG. 69. A method employed by Lodge for connecting the receiving apparatus to the antenna.

These contrivances of Lodge and of Lodge and Muirhead seem not to have been developed by them experimentally to their natural completion, which would perhaps have led to one or the other of the types given in Figs. 64 and 65. They did come to one of these types much later, but only after Mr. Marconi and Professor Ferdinand Braun had published their descriptions of the coupled circuits, and by various public demonstrations and polemics had shown the great advantage of the coupled circuits.

Just a word as to Lodge's wing-shaped vanes at the transmitter and receiver. These are an enlarged oscillator and resonator preserving the symmetry of Hertz's original apparatus. In practice they have not been much used in this symmetric form, probably on account of the difficulty of giving to the apparatus sufficiently large dimensions when both vanes have to be supported vertically in an elevated position. In practice, Lodge and Muirhead early replaced the bottom vane and sometimes also the top one by the alternative, horizontally-placed conductor, consisting of a sheet of wire netting. The spark gap, instead of being halfway between these conductors, is usually nearer the lower conductor, as shown in Fig. 70, with an inductance *L* added below the gap, for preserving approximate electrical symmetry and for tuning.

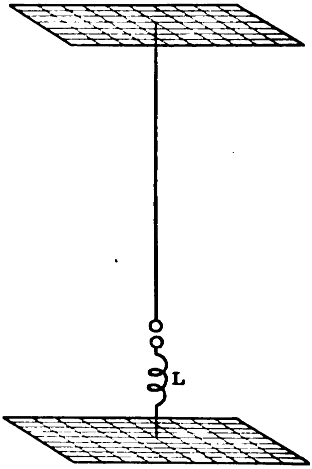

FIG. 70. Elevated conductor and ground of wire netting (Lodge).

In addition to these various suggestions by Lodge in regard to the use of tuning coils and transformers in the circuits, and the maintenance by him of the possibilities of the ungrounded circuits, Professor Lodge, together with Messrs. Muirhead and Robinson, has also devised a new form of coherer. This is described in Chapter XVI.

The Coupled Circuits of Ferdinand Braun. — Let us return to the matter of the coupled circuits. In a German patent, No. 111,578, applied for October 14, 1898, Professor Ferdinand Braun of Strassburg in Germany describes "a

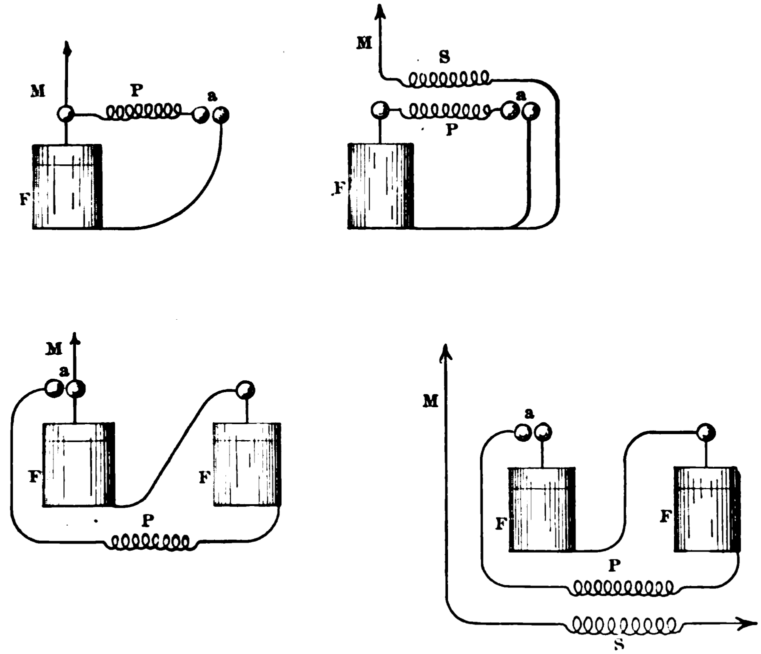

FIG. 71*a*, 71*b*, 71*c*, 71*d*. Professor Ferdinand Braun's methods of coupling a condenser circuit to an antenna.

form of connection for an oscillator coupled with an air-wire for spark telegraphy." He proposes to use in this invention, which is a sending apparatus, the waves which are produced by the "discharge of Leyden jars in the presence of induction coils."

The accompanying Figures, 71_a, 71_b, 71_c, 71_d, are taken from Braun's patent specifications.

In 71_a "*F* is a Leyden jar, *a* the spark gap, *P* an inductance coil and *M* the emitting wire."

In 71_b "the form of connection is so changed that a primary and a secondary coil are used, so that in the circuit of the emitter *M* a coil only is present."

Fig. 71_c "shows two Leyden jars connected one behind the other in so-called cascade connection, and"

Fig. 71_d "shows the same connection for the use of a transformed current."

In examining these figures it should be borne in mind that the two coils *P* and *S*, which for simplicity of drawing are shown side by side, are really wound one around the other so as to form an oscillation transformer.

It should also be borne in mind, while reading the specifications, that Professor Braun means primarily to describe a method of connecting the Leyden-jar circuit to what he calls the air-wire circuit, and that the document does not purport to give a description of a complete sending apparatus. This is clear from his single *claim* at the end of his description. His claim is a "form of connection of an oscillator coupled with an air wire for spark telegraphy, characterized by an oscillation circuit containing a Leyden jar and a spark gap, to which the air wire for sending out the waves is connected either directly or by means of a transformer, for the purpose of bringing by this means greater quantities of energy into action."

His clear understanding of how this energy may be increased is evident from a paragraph of the specification which says: "Above all, the slower oscillations have the advantage that their energy may be increased by increasing their potential amplitude (by transformation) as well as by increase of capacity and by the use of powerful sources of electricity." The gain of energy by increasing the potential could not be attained with an emitter having the spark gap directly in the antenna, because there is a certain "active" spark length that cannot be exceeded. This is pointed out in the specifications.

However, in neither the German nor the corresponding American patent, filed Feb. 6, 1899, does Professor Braun speak of the necessity of properly attuning the secondary circuit to the period of the condenser circuit, which is a prerequisite for attaining the high potential in the antenna circuit, and without this attuning of the secondary to the primary circuit, the large capacity of the primary condenser and the use of powerful sources of electricity would not give any advantage over the simple Marconi antenna.

The first mention by Braun of the required tuning, so far as I have been able to find, is in a publication of the 5th of March, 1901, in the *Physikalische Zeitschrift*, Vol. 2, p. 373, and in a book by Braun entitled *Drahtlose Telegraphie durch Wasser und Luft*, published in 1901.

In examining Braun's patent drawings one may wish to know whether the antenna circuit is to be grounded or otherwise balanced by a capacity at the other end of the secondary. Nothing is said on this subject in the German patent, but in the corresponding American patent he says, with reference to Fig. 71*d*, that "one end of the secondary coil of the transformer *S* is connected with the transmitting wire *M*, and the other end is shown prolonged and ending in an arrow to indicate that it may be prolonged by adding a suitable length of insulated wire or connected to some other capacity area." In his book of 1901 a corresponding prolongation or addition of capacity is indicated in his drawing of the direct coupled circuit, as is shown in Fig. 72.

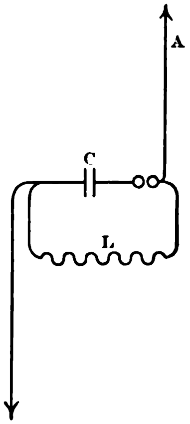

Fig. 72. Form of direct coupled transmitter devised by Ferdinand Braun.

There is nothing in these early patents of Professor Braun relating to coupled circuits at the receiving station. The coupled receiving circuits were undoubtedly invented by Marconi, and also his description of the inductively coupled sending station, though of published date a little later than that of Braun, is a much fuller and a more complete disclosure of the invention. The work of Marconi in developing the coupled circuits will now be discussed.

Marconi's Coupled Circuits. — Mr. Marconi, in an English patent applied for June 1, 1898, clearly sets forth the transformer arrangement for a *receiving station.* This is shown in Fig. 73, in which *A* leads to the antenna, and *E* to earth. The coils J^1J^2, which are represented as side by side, are the oscillation transformer and are really wound one around the other. The primary J^1 is connected to the antenna and the earth; while the secondary is in circuit with the coherer *T* and the condenser K^1. A relay *R* and battery *B* are connected about the coherer through the choking coils c^1c^2. This is, therefore, a clear presentation of the inductively connected receiving station.

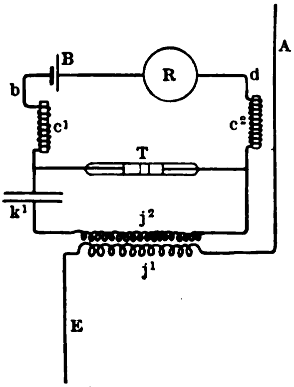

FIG. 73. Marconi's inductively coupled receiving circuit.

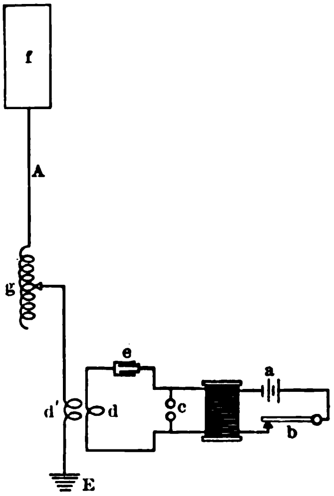

FIG. 74. Marconi's inductively coupled transmitter.

In 1900 Marconi was granted an English patent for an *inductively coupled sending station* also. This is shown in Fig. 74, and is of the typical form of our Fig. 64, with, however, an added variable inductance *g* in the antenna.

In the 1900 description of this apparatus Mr. Marconi clearly points out the necessity of having the primary and the secondary circuits at the sending station and the corresponding circuits at the receiving station adjusted to resonance with one another. He says: " The capacity and self-induction of the four circuits — i.e., the primary and secondary circuits at the transmitting station and the primary and secondary circuits at any one of the receiving stations in a communicating system — are each and all to be so independently adjusted as to make the product of the self-induction multiplied by the capacity the same in each case or multiples of each other — that is to say, the electrical time periods of the four circuits are to be the same or octaves of each other."

The advantages of the coupled circuit at the sending station, according to Signor Marconi, arises in "the approximately closed circuit of the primary being a good conserver and the open circuit of the secondary being a good radiator of wave energy."

The variable inductance *g* in Fig. 74 placed in the antenna of the sending circuit and a corresponding coil at the receiving station were used to aid in this process of tuning.

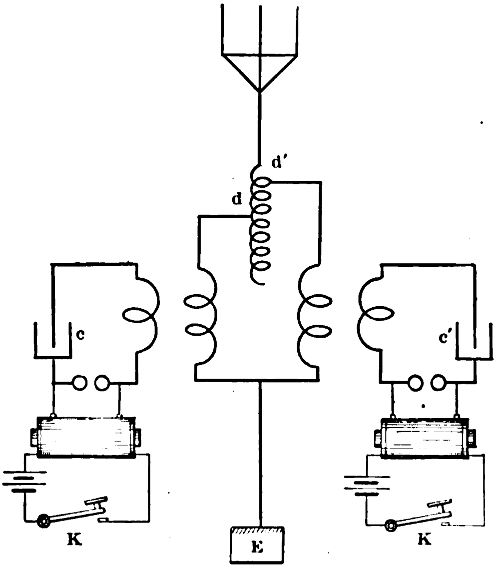

FIG. 75. Apparatus used by Marconi for sending two messages at once.

A sending and a receiving station devised by Mr. Marconi for sending or receiving two messages at once with the use of a single antenna are shown in Fig. 75 and Fig. 76. This was successfully employed and exhibited by Marconi in the autumn of 1900. Two operators at the two keys *K* and *K* of the sending station made the signals. The two condenser circuits having different values of capacity and self-inductance were independently charged, and discharged with different periods of oscillation. These two periods were both impressed on the antenna through circuits which by means of the antenna inductances *d* and *d'* were made to resonate with the respective condenser periods. At the receiving station, Fig. 76, the waves constituting the double message acted on the receiving antenna. The waves of the shorter period induced oscillations through the antenna and through the right-hand primary to the earth; while the oscillations of longer period passed through the circuit to the left, which contained the greater inductance in the antenna circuit. The two periodic disturbances, thus separated, act inductively on their properly tuned coherer circuits, and give up the two messages without confusion to the two receiving instruments. This duplex wireless telegraphy can be carried on only provided the wave lengths of the two sending stations are not too nearly equal.

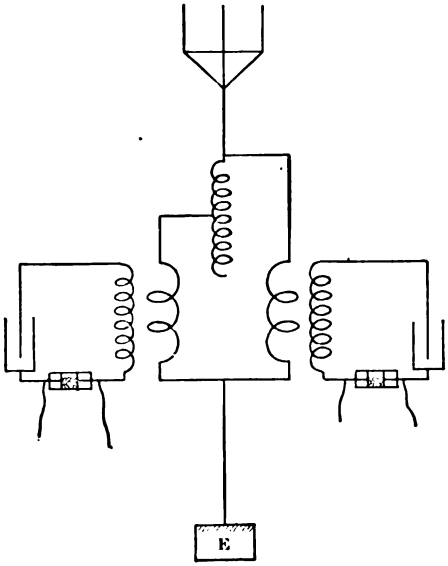

FIG. 76. Marconi duplex receiving apparatus.

Some very notable achievements were made by Mr. Marconi with these resonant circuits in 1901 and 1902.

A sending station of great power was completed at Poldhu in Cornwall, England, in 1901. In December of that year signals were reported to have been sent across the Atlantic Ocean from Poldhu to Cape Race near St. John's in Newfoundland. The signals, which consisted of the letter " S " repeated at stated intervals, were said to have been clearly received at Cape Race, by means of a receiving antenna consisting of a copper wire 400 feet long supported by a kite. The detector employed in the transatlantic experiments was an instrument known as the "Italian Navy Coherer," and consisted of a globule of mercury between iron terminals in a glass tube. This form of detector is self-restoring, and with it a telephone receiver in series with a battery is used in the local circuit in the place of the ordinary telegraph relay.

In March, 1902, messages sent out from Poldhu were received by the Marconi apparatus on board the steamer *Philadelphia* when the steamer was 1550 miles (2400 kilometers) from the sending station. In December of the same year Marconi announced the transmission of three entire messages from Glace Bay, Nova Scotia, to Poldhu in England, a distance of 2300 miles.

On January 19, 1903, the powerful Marconi station at Wellfleet, Cape Cod, Massachusetts, transmitted to Poldhu, England, the following message from the President of the United States to the King of England:

> "HIS MAJESTY, EDWARD VII,
> *London, England.*
>
> In taking advantage of the wonderful triumph of scientific research and ingenuity which has been achieved in perfecting a system of wireless telegraphy, I extend on behalf of the American people most cordial greetings and good wishes to you and to all the people of the British Empire.
>
> THEODORE ROOSEVELT."
>
> WELLFLEET, MASS.,
> January 19, 1903.

This message, though intended to be relayed at Cape Race, was received, according to reports issued by the Marconi Company, direct at the Poldhu station in England.

CHAPTER XIV

NATURE OF THE OSCILLATION. THE GROUNDING OF CIRCUITS

In the two preceding chapters, devoted to a period of invention and rapid development of wireless telegraphy, several important facts have been introduced with only casual examination. Among the questions there raised the most interesting is perhaps the question of the rôle played by the earth. This question has two aspects.

First, it has been seen that both grounded and ungrounded oscillators have been employed. What is the relation between these two forms of oscillator, and what effect has the ground connection on the nature of the vibration?

Second, it has been apparent from the great distances attained, in the transmission of messages entirely across the Atlantic Ocean that the electric waves are not lost to the receiver by reason of the curvature of the earth, even when the two stations are separated by a distance that is a considerable fraction of the earth's whole circumference. How is it that the electric waves are propagated from one station to the other, and how does the earth contribute to the process?

These two questions, dealing with the nature of the vibration and the manner of the propagation of the waves, will be considered respectively in this chapter and in the next chapter. As introductory, we shall need first to consider the oscillations occurring in a simple ungrounded Hertz oscillator.

Current and Potential in a Hertz Oscillator. — Suppose the Hertz oscillator to consist of two metallic rods or wires with a spark gap between, and suppose the two halves of the oscillator to be charged, the one positive and the other negative, as shown in the first diagram, (*a*), of Fig. 77, in which the shaded area attached to the upper half of the oscillator is taken to indicate positive electricity, while the unshaded area attached to the lower rod indicates negative electricity. These areas are made rectangular to show that there is at the beginning a uniform distribution of the two electricities respectively on the two rods.

If the electrostatic capacity per unit of length of the rods is uniform throughout both rods, which is approximately true, when the rods are not too short the potential of the conductor at any point of its length will be proportional to the charge, so that the shaded area representing a distribution of positive *charge* may also be looked upon as showing the distribution of positive *potential*, while the unshaded area represents negative potential. Thus, in the condition depicted in diagram (*a*), there is a uniform positive potential over

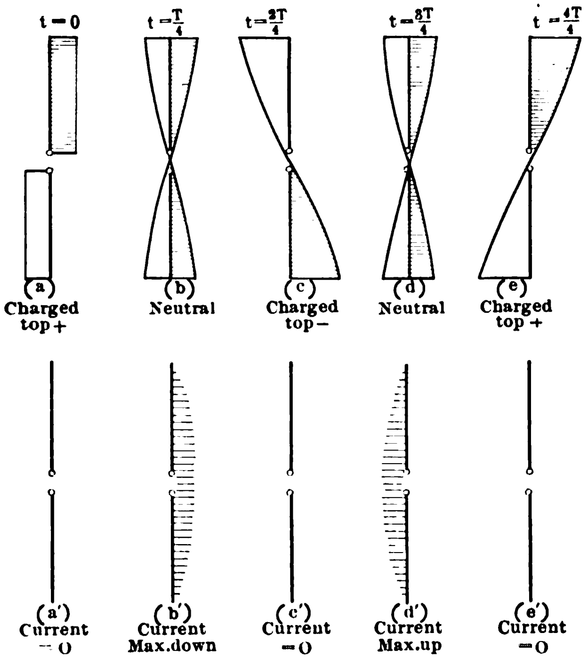

FIG. 77. Potential and current distribution.

the top rod, and a corresponding negative potential over the bottom rod. This is before the spark begins.

Suppose, now, the spark to start between the rods; the gap between the rods becomes conductive, and a current begins to flow between the rods. There is a flow of positive electricity from the top rod and a flow of negative electricity from the bottom rod. The electricity to flow first across the gap is that in the neighborhood of the spark gap, because it is there that the potential gradient is greatest. After a short time — one-fourth the period of a complete oscillation — the condition of the charge, and likewise the potential, of the rod will be that condition represented in diagram (*b*), in which one-half of the positive electricity has gone into the lower rod, and half the negative electricity has gone into the upper rod, giving both rods equal quantities of positive and negative electricity, so that both rods are neutral. Why, then, does not the action cease?

In order to be able to see why the action does not cease when the charge has become neutral throughout the oscillator, we must take into consideration the *current* in the conductor as well as the charges. The second row of diagrams of Fig. 77 represents the current at the epochs corresponding to the potential representations of the first row.

At the beginning the potential, or charge distribution, is shown by diagram (*a*) of the top row. At the same time no current is flowing, which fact is represented by the inactive oscillator shown at (*a*′) of the second row. The current is now supposed to begin. It cannot spring to its final value at once, because the increase of the current builds up a magnetic field surrounding the oscillator, and this growing magnetic field produces an electromotive force in the conductor opposing the growth of the current. Time is thus required for the current to become established. At a time equal to one-fourth the period of complete oscillation, $t = T/4$, the current has grown to its maximum value, which is represented at (*b*′). The shading to the right of the conductor is meant to represent the magnitude of the current at each point of the conductor, though the current is *along* the conductor and not perpendicular to it, as the shading is. It is interesting to note that the current is not uniform throughout the length of the conductor. The current is greatest near the middle of the conductor, and is zero at each end. The reason that it is greatest at the middle is that the current flowing out from the center toward either end decreases by reason of the charge that it leaves along the conductor *en route*. At the very end of the conductor the current is zero, because no electricity flows out beyond the end and none flows in from beyond the end. We have thus in the conductor a distribution of current like that of (*b*′) — large in the middle and zero at both ends.

Thus, at the time $t = T/4$, the conductor is in a neutral condition with respect to charge, but is being traversed by a current in a downward direction. This current is a maximum with respect to time, for the next instant the positive electricity in the lower rod begins to be in excess. This calls into play an opposing electromotive force, and diminishes the current, which, however, cannot cease at once, because any diminution of the current diminishes the surrounding magnetic field, and gives an electromotive force tending to preserve the current. The current thus continues to pile up a positive charge on the lower rod, in spite of the fact that this piled-up charge is exerting a restoring force.

Presently, however, this restoring force, which has gone on increasing, brings the current to a stop. Then when there is no current, there is no magnetic field, and the accumulated positive electricity on the lower rod starts the current upward. This reversal of the current occurs at a time $t = T/2$; and the condition of the charge and current is represented at (*c*) and (*c'*). The upward current continues to flow, and produces successively the conditions (*d*) and (*d'*), at $t = 3T/4$, and (*e*) and (*e'*) at $t = T$.

In the last named state the upper rod is entirely positive, while the lower rod is entirely negative. This resembles the initial state of the rod, but is not identical with it, because the initial state was brought about by an extraneous slow charging source (Holtz machine or Ruhmkorff coil) instead of by the very rapid surging that is going on in the oscillator when it is oscillating with its own natural period.

From the condition of initial uniform distribution we have followed the charge and current, by rather large stages of a quarter of a period each, through a single oscillation. The charge on the conductor will continue to oscillate, going through the successive steps several times — the accumulation of electricity becoming less and less at each oscillation until the spark extinguishes.

Nodes and Loops of Potential and Current. — From the preceding discussion it is apparent that the two ends of the Hertz oscillator undergo maximum fluctuations of potential, and are, therefore, *loops of potential.* The middle of the conductor during the oscillation has no accumulation of charge on it; the potential of the middle, therefore, never rises above zero (after the start), and is a *node of potential.*

On the contrary, the *nodes of current* are at the ends of the oscillator, while a *loop of current* is at the middle of the oscillator.

EXPERIMENTS ON THE DISTRIBUTION OF CURRENT IN AN UNGROUNDED HERTZ OSCILLATOR

In the preceding dicussion there was given a theoretical examination of the nature of the potential and the current distribution occurring in a Hertz oscillator. I have recently made a simple experiment that approximately confirms the deductions there given in regard to the current.

The Principle of the Experiment and a Description of the Oscillator. — The principle of the experiment is illustrated in Fig. 78. Instead of making a breach at various points in the oscillator and inserting therein an instrument for determining the current, this current at different points in the oscillator was studied by means of its inductive action on a small neighboring circuit *WM* placed successively at different positions along the oscillator, as indicated by the dotted squares in Fig. 78. The spark gap of the oscillator is shown at *G*. The two conductors of the oscillator *OO*, were each a wire 1 mm. in diameter and 9 meters long, supported horizontally 1 meter above the wooden floor of a long room in the third story of the laboratory. The oscillating system was thus at a height of about 10 meters above the surface of the earth, and was probably very little disturbed by the capacity of the earth. The oscillator was supported by three insulating stands, — one at the spark gap and one at each end of the wire. The central stand for supporting the spark gap carried also a storage battery and a small Ruhmkorff coil for charging the oscillator.

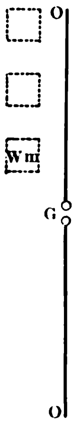

Fig. 78. Plan of apparatus for exploring current distribution.

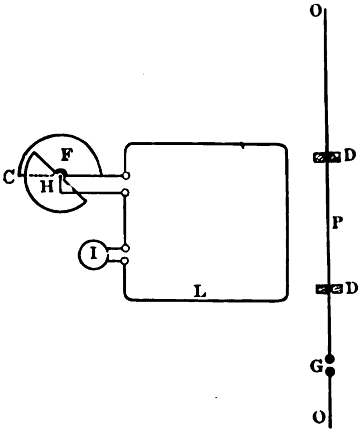

Fig. 79. Detail of exploring circuit.

The Exploring Circuit. — An enlarged view of the apparatus, showing details of the exploring circuit by which the measurements were made, is given in Fig. 79. This circuit, shown at the left of the oscillator, consists of a square loop of heavy copper wire,

L, 30 cm. on a side, and having in series with it a variable condenser C and a high-frequency current-reading instrument at I. I shall now describe the instrument I and the condenser C.

Description of the Instrument. — The instrument at I as is shown in Fig. 80 consists of a disc of silver, suspended by a fine fiber of spun quartz so as to hang near a small coil of a few turns of wire, with which the disc made an angle of 45 degrees. The disc is at M, and the coil, which in this experiment consisted of five turns of wire wound on a vulcanite tube, is shown at C, Fig. 80. The two ends of the coil are connected to binding posts, by which the coil is put into the circuit. The front of the disc carries a small mirror, enabling the deflections of the disc to be measured by means of a telescope and scale such as is used with delicate galvanometers.

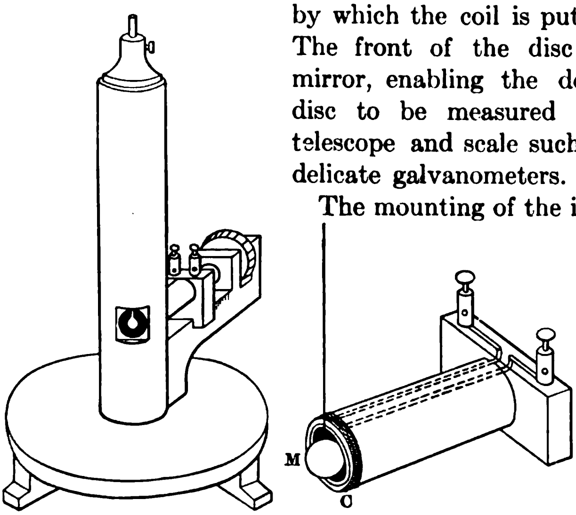

Fig. 80. High-frequency dynamometer. Mounting shown at left, suspension at right.

The mounting of the instrument is also shown in Fig. 80. The disc is suspended in the vertical vulcanite tube, which is mounted on leveling screws; the support of the coil is inserted in the side of the vertical tube, and is arranged to be moved in and out by a micrometer screw. This delicate motion of the coil in or out brings the coil nearer to or farther from the suspended silver disc so as to vary the sensitiveness of the instrument, to make it suitable for measuring small or large oscillating currents.

The action of the instrument, which we shall call a "high-frequency dynamometer," is as follows: oscillations in the coil induce oscillations in the disc. Between these two sets of oscillations there is a force which causes the disc to tend to set itself at right angles to the coil.[1] The deflections of the dynamometer are proportional to the square of the current through it.[2]

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[1] The principle of this instrument was independently discovered by Dr. Elihu Thomson and by Professor Fleming. The instrument was first shown

The Variable Condenser. — Returning to Fig. 79, the loop *L* contains, besides the high-frequency dynamometer *I*, a variable condenser *C*. This condenser is of a form much used in wireless telegraphic apparatus, and is described by Korda in German Patent No. 72447, issued Dec. 13, 1893. It consists of two sets of semicircular plates, — one set *F* being connected together and fixed in position, and the other set *H* being also connected together and capable of rotation about a central axis. By rotating the plates *H* so as to bring a greater or less area of the two sets of plates into interlapping position, the capacity of the condenser can be varied. The position of the plates *H* with respect to *F* can be read on a scale attached to the top plate of *H* and passing under a fixed pointer. A photograph of a condenser of

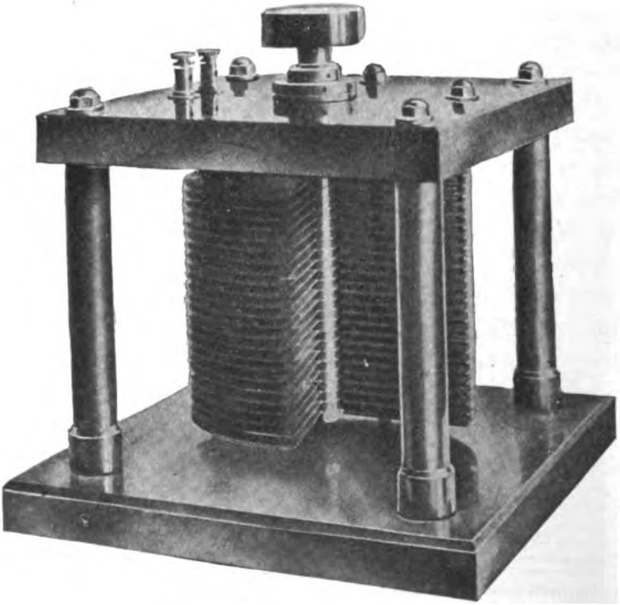

FIG. 81. Korda air condenser.

to be applicable to the measurement of oscillating currents of high frequency by Messrs. Northrup, Pierce and Reichmann, and has been used in the present improved form by the author in a large number of resonance experiments, some of which are later to be described in this volume.

[2] A theoretical and experimental proof of this proposition is given by the author in Phys. Review, Vol. 20, p. 226, 1905.

this character, with capacity somewhat larger than that of the condenser employed in these experiments, is shown in Fig. 81.

Large Current at Resonance. — Variations of the capacity of *C* varies the natural period of oscillation of the condenser circuit, and when this period is made equal to that of the Hertz oscillator *OGO*, a maximum deflection of the instrument *I* is obtained, under the action of the oscillation.

The resonant condenser circuit when calibrated in terms of wave length is a form of "wave meter." How this calibration is effected will be shown later.

Exploration of Current Distribution. — Since the wave meter in this form, on account of the instrument *I*, is not conveniently movable, it was necessary to move the oscillator in order to explore the distribution of current in the oscillator. The oscillator, with its exciting induction coil and storage battery, was moved lengthwise, keeping it always the same distance from the wave meter, by means of the vulcanite guides *DD* of Fig. 79. Readings of the dynamometer were taken for various positions of the oscillator with respect to the wave meter. This was equivalent to moving the wave meter along the oscillator, and the readings of the dynamometer were proportional to the square of the current in the wave meter, and therefore proportional to the square of the current at different points of the oscillator; because the induced current, keeping everything else the same, is proportional to the inducing current.

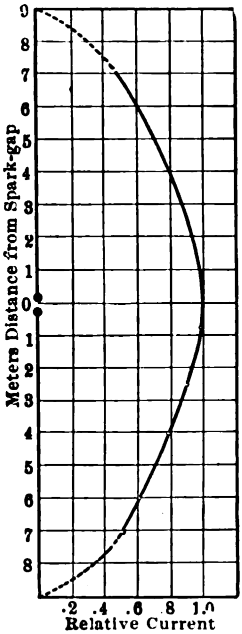

FIG. 82. Distribution of current along a Hertz oscillator, as determined by experiment.

The results obtained for the distribution of the current in the oscillator are plotted in Fig. 82. The curve of Fig. 82 shows that the current in the oscillator is greatest near the gap and falls off to zero at the ends of the oscillator in a manner not very different from that shown in the theoretical drawings of Fig. 77. There is a loop of current in the middle and a node at each end of the oscillator.

EXPERIMENTS ON THE WAVE LENGTH OF THE UNGROUNDED HERTZ OSCILLATOR

Wave Length of the Hertz Oscillator. — Having investigated the distribution of current and potential in an ungrounded oscillator, let us next inquire what is the wave length of the electric wave emitted by such an oscillator.

With an oscillator of *two parallel wires* near together, as shown in Fig. 83, the length of the wave is very approximately four times the length of one of the wires, *GBC*. If now we take the two parallel wires, separate them, and extend them out oppositely to each other from the gap so as to form the Hertz oscillator, does the wave length remain the same; namely, $\lambda = 4\,l$, where λ is the wave length and l is the length of the half-oscillator? Some theoretical writers (for example, Abraham [1]) say that it does remain equal to $4\,l$; while Macdonald [2] has computed λ in this case to be $5.06 \times l$.

Recently Messrs. Webb and Woodman,[3] for very short oscillators, with a half length l between 1 and 5 cm., have obtained experimentally the relation $\lambda = 4.8\,l$.

For oscillators of half length between 1 and 3 meters, F. Conrad [4] has obtained the values presented in the accompanying table, with the average relation $\lambda = 4.24\,l$.

CONRAD'S TABLE FOR RELATION OF λ TO l

l Half length of oscillator in meters.	λ Wave length in meters.	$\frac{\lambda}{l}$
1.00	4.20	4.20
1.92	8.00	4.17
2.00	8.40	4.20
2.75	12.0	4.37
3.15	13.4	4.25
	Average	4.24

The experiments of Conrad and those of Messrs. Webb and Woodman both give evidence of being very careful experiments,

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[1] M. Abraham, Wied. Ann., Vol. 66, p. 435, 1898.

[2] Macdonald, Electric Waves, p. 111.

[3] Webb and Woodman, Phys. Review, Vol. 29, p. 89, 1909.

[4] F. Conrad, Drude's Ann., Vol. 22, p. 670, 1907.

and we must therefore conclude that the ratio of λ/l for very short oscillators is greater than for the long oscillator.

We are primarily interested in the long oscillators, and in order to extend the experimental records to the case of longer oscillators than those studied by Conrad, I have made a series of measurements with the apparatus of Figs. 78, 79, 80.

Calibration of the Wave Meter. — The wave meter was calibrated for various adjustments of the condenser C by setting it to resonance with various lengths of the two parallel wires of Fig. 83, as had been previously done by Drude. With the wave meter calibrated to read directly in wave lengths, the parallel calibrating wires were removed, and the Hertz oscillator, consisting of two oppositely extending wires of various lengths (1 mm. in diameter), was brought up near the wave meter, and the wave length produced by the oscillator was determined. The results obtained are given in the following table:

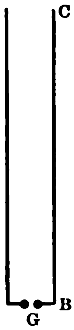

FIG. 83. Parallel-wire oscillator for calibrating wave-meter for short wave-lengths.

AUTHOR'S TABLE OF RESULTS FOR RELATION OF λ TO l

l Half length of oscillator in meters.	λ Wave length in meters.	$\frac{\lambda}{l}$
4.0	16.9	4.22
4.5	18.9	4.20
5.	21.2	4.23
5.5	23.2	4.22
6.	24.9	4.15
7.	29.5	4.21
8.	33.6	4.20
9.	38.7	4.23
10.	41.6	4.16
11.	46.1	4.22
12.	49.5	4.13
13.	53.9	4.14
14.	57.5	4.11
15.	63.0	4.19
	Average	4.19

The average of the results obtained by the author for the ratio of λ to l, namely, $\lambda/l = 4.19$, for wave lengths between 17 and 63 meters, is a little less than the corresponding ratio, 4.24, obtained by Conrad for wave lengths between 4 and 13 meters. The difference is only 1%.

From these results we may conclude that the wave length produced by a Hertz rectilinear oscillator is very approximately 4.20 times the length of one limb of the oscillator, provided this limb is greater than 1 meter long and of comparatively small diameter.

Let us next see how the vibration of a conductor is modified when one end is connected to earth.

ON GROUNDED CIRCUITS

Grounded Circuits. Image Theory. — Suppose now the lower limb of a vertical Hertz oscillator to be cut away close up to the spark gap and be replaced by a connection to earth. According to electrical theories, if the earth were a perfect conductor, the electrical wave length of the earthed system would be the same as that of the Hertz oscillator,— the earth merely taking the place of the other half of the Hertz oscillator. The earthed system, which is a simple Marconi emitter, would have the same distribution of current and potential in the antenna as the upper half of the Hertz oscillator had before removing the lower limb.

In order to examine this theory, let us confine our attention in the beginning to a receiving station, and suppose that we have there simply an ungrounded rectilinear conductor isolated in space, and placed parallel to the electric force of the incoming waves. Let the length of this straight-line conductor be so chosen that its natural period of electric oscillation is equal to the period of the waves. The distribution of current in the conductor would resemble that shown in Fig. 82.

If we could introduce a current reading detector into the circuit without disturbing the conditions, the instrument would give a maximum reading when placed at the center of the receiving conductor; this is the point at which the fluctuation of potential is zero.

Suppose with such an instrument in the circuit we should cut away the lower half of the conductor; the reading would become zero, because there would be no capacity out beyond the instrument into which the current could flow. If now a capacity is attached to the instrument in the place of the removed conductor, some current would flow between the straight wire and the capacity and register in the instrument.

If the capacity attached were very large (e.g. the earth), the point of zero fluctuation of potential would again be brought near the instrument, because a large fluctuation of potential cannot occur in a very large capacity under the action of the currents with which we are concerned. We should, therefore, have the same current as when the conductor was made up of two parts symmetrical about the instrument.

In actual systems, the grounding may be imperfect. In that case the symmetrical image would give only approximately an equivalent system.

I have made some experiments to test this image theory of the action of the ground connection. The experiments consisted in comparing resonance curves taken with various forms of grounded circuits with the corresponding resonance curves taken with an image circuit in the place of the ground. Two of these experiments are here briefly described.

EXPERIMENTS TO TEST IMAGE THEORY OF THE GROUND

Experiment I. The Aerial Circuit and its Image Tuned by Variable Inductances. — In testing the image theory of the action of the ground at the receiving station the form of circuit shown in Fig. 84 was employed. The high-frequency dynamometer described on p. 113 was used for detecting and measuring the minute oscillating currents at the receiving station, and was placed at *I*

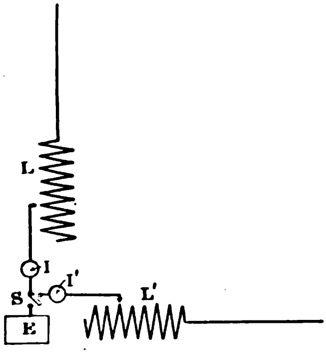

FIG. 84. Circuit employed in study of the image theory of the ground.

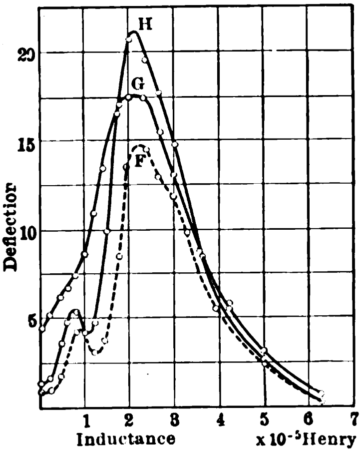

FIG. 85. Resonance curves in study of the image theory of the ground. Curve *H* was obtained with horizontal duplicate of antenna; curve *G*, with ground.

in series with a variable inductance and a vertical antenna 23.2 meters long. This aerial system, by means of a switch at S, could be connected to the ground E, or the ground could be thrown off and replaced by metallic parts duplicating the aerial system. The duplicate was, however, not an exact theoretical image of the aerial system, because the second antenna had to run off horizontally instead of straight down.

The horizontal wire was made equal in length to the vertical antenna, 23.2 meters, and was supported about 1 meter from the ground by cords attached to posts. In series with the horizontal wire was a variable inductance L' duplicating the tuning coil L, and a small coil I' of fine wire duplicating the coil of the receiving instrument.

Curves giving the results of the experiment are shown in Fig. 85. For curve G the grounded circuit was used, and deflections of the receiving instrument were taken for various values of the inductance of the tuning coil L; the deflections are plotted against values of L.

The switch S was then thrown so as to connect the receiving circuit to the horizontal system instead of to the ground. With this arrangement the curve H was obtained. In taking this curve, the tuning coil L and its image L' were *kept identical and varied together*. The curve H, therefore, shows the deflections of the receiving instrument plotted against the common values of L and L'.

Discussion of Results in Experiment I. — The two curves G and H of Fig. 85 are seen to have their maxima for the same value of inductance. That is, a given value of inductance, 2.1×10^{-5} henries, gives a maximum deflection in the case of the grounded circuit. To obtain a maximum with the duplicated system the same inductance 2.1×10^{-5} henries must be used in *both the vertical circuit and in its horizontal duplicate.* The result is a confirmation of the image theory of the grounded circuit. The earthing of the circuit gives it the same period of vibration as the duplication of the aerial system gives.

It is interesting to note that *the deflection (current square) is about* 20% *larger with the duplicated system than with the grounded system* — a fact that may be accounted for by supposing a higher resistance with the grounded system than in the wholly metallic system.

Some other facts in regard to the experiment are discussed in the original publication.[1]

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[1] G. W. Pierce: Resonance in Wireless Telegraph Circuits. Part IV, Physical Review, Vol. 22, p. 174, 1906.

The curve *F*, with which we are not here concerned, was obtained with the duplicate antenna wound around the house of the receiving station.

Experiment II. Quarter-Wave Ground. — What was perhaps a more interesting experiment confirmatory of the image theory of the ground was made by replacing the ground by a horizontal wire of which the length could be varied. The relative amounts of energy received (deflections) for different lengths of the horizontal wire are shown in the curve *A* of Fig. 86. Resonance was obtained when this wire had the length of 38 meters, which was very close to one-fourth the wave length (153 meters). The ground gives the system the same period as an added quarter-wave wire gives the system. Curve *B* obtained with different conditions leads to the same results.

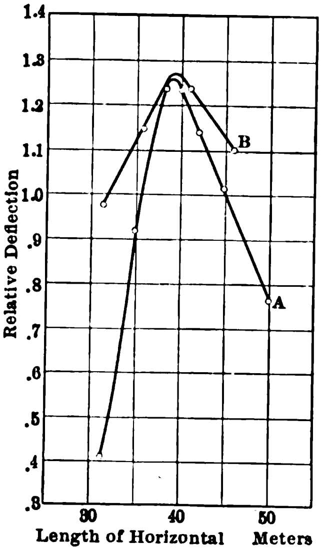

Fig. 86. Showing that the ground may be replaced by a quarter-wave wire.

Conclusion from the Experiments. — These experiments I and II show that the effect of the ground, so far as concerns the vibration in the antenna, is to introduce into the circuit at the ground a point of zero fluctuation of potential, — an effect that can also be obtained with an artificial ground consisting of a symmetrical duplicate of the aerial system or consisting of a horizontal wire not far from the earth and of length equal to one-quarter of the wave length to be received.

Professor Ferdinand Braun at a date earlier than that of my experiments has suggested the use of horizontal wire in replacement of the ground and also the use of a capacity consisting of a large cylindrical conductor in the place of the ground. He has not, however, so far as I know published any quantitative results on the subject.

CHAPTER XV

PROPAGATION OVER THE EARTH

The Propagation of the Waves over the Surface of the Earth. — In the preceding chapter it was shown that so far as concerns the wave length and the distribution of current and potential, the grounding of an antenna was equivalent to attaching it to its image.

Let us discuss further this idea with reference now to the manner of propagation of electric waves over the surface of the earth. Does the earth contribute to the propagation of the waves in an advantageous or only in a detrimental way ?

We shall begin this discussion with the assumption that the earth is a perfect conductor. With this assumption we can apply to the problem further reasoning based on Sir William Thomson's theory of electrical images.

Theory of Images. — Suppose we have two small bodies *A* and *B* with equal charges of electricity of opposite signs. The direction of the electric force between *A* and *B* is represented by the curved lines in Fig. 87. A plane *P* drawn everywhere equally distant from *A* and *B* will be a surface of zero potential.

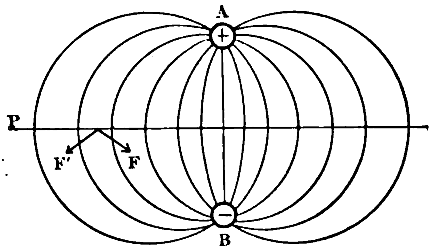

FIG. 87. Lines of electric force between two oppositely charged bodies *A* and *B*. The plane *P* is at zero potential.

The proof that *P* is a surface of zero potential is as follows: The potential of a point is the work required to be done in order to bring a unit positive charge up to the point from an infinite distance. Now a unit charge of positive electricity can be brought up to any point of the plane *P* without doing any work; because the force at any point of the plane, being made up of an attraction *F* due to *B* and an equal repulsion *F'* due to *A*, exerts a force perpendicular to the plane, but no force along the plane. The force is therefore perpendicular to the direction of motion when the charge is brought up along the plane, and the work done is therefore zero. For further details in regard to work and potential see Appendix I.

Having shown that the plane *P* is everywhere at zero potential, let us next introduce the idea well established in treatises on electricity, that so long as we keep the potential of the plane *P* equal to zero the electric force in the region between *A* and the plane *P* is completely fixed, no matter what changes we may introduce below the plane. If, then, the lower half of the diagram is removed and the plane is in some other way kept at zero potential, the electric force between *A* and the plane will be the same as before; namely, that represented in Fig. 88, which is the upper half of Fig. 87. We may keep the plane at zero potential by grounding it so that it comes into coincidence with the surface of the earth; or the surface of the earth itself may take the place of the plane, provided the earth for a considerable area around the charged body *A* is a good conductor.

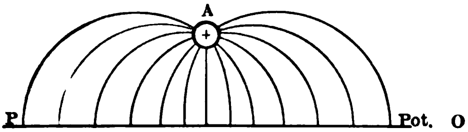

Fig. 88. Lines of electric force between a charged body *A* and an infinite conducting plane kept at zero potential.

That is to say, if the earth's surface is a good conducting plane for a considerable extent, and a charged body *A* be placed above the surface of the earth, the field of electric force between *A* and the plane surface of the earth will be the same as the upper half of the field between *A* and a body *B*, which has a charge equal to *A* and opposite in sign, — *B* being at the distance below the plane that *A* is above it. This equal opposite charge symmetrically placed in regard to the plane is called *the electrical image of A* in the plane.

Similar Theory Applied to the Oscillator. — If we next consider the case of the electric oscillator, the field of electric force for the symmetrical oscillator, as we have seen in Chapter VIII, is roughly that represented in Fig. 89. The ideal, nonmaterial plane *PP* through the figure is at zero potential, so that the lower half of the diagram could be replaced by the surface of the earth, if it were plane and perfectly conductive, without disturbing the upper half of the figure. Whence it follows that *the oscillation and radiation from an oscillator grounded to an infinite, plane, perfect conductor is the same as the oscillation and radiation of the upper half of a symmetrical Hertz oscillator.* The nature of the wave sent out from an oscillator so grounded is represented in Fig. 90.

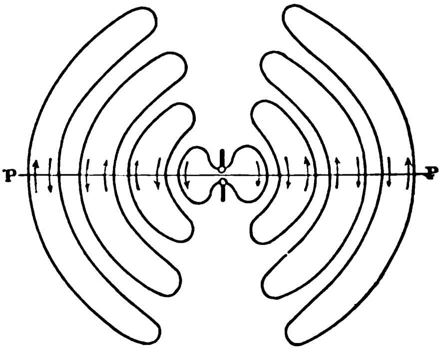

FIG. 89. Lines of electric force about a Hertz oscillator.

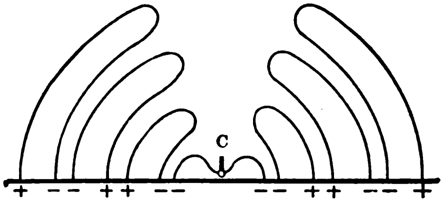

FIG. 90. Lines of electric force about a half-oscillator discharging to a perfectly conductive ground.

Guided Electric Waves. — Figure 90 shows approximately the theoretical mode of propagation of the electric wave over those parts of the surface of the earth where the earth is a good conductor. The loops there shown receding from the oscillator are lines of electric force. Now a line of electric force must be either a closed line, as in Fig. 89, or must terminate at one end on a positive charge and at the other end on an equal negative charge. There is, therefore, a series of successive positive and negative charges induced in the surface of the earth, and these positive and negative charges move with the wave with the velocity of light. The earth thus serves as a guiding conductor and causes the loops of electric force terminating on it to follow the surface of the earth. This accounts for the fact that communication is possible between stations which on account of the intervening curvature of the earth are not visible from each other. We have here a simple view of the matter, obtained on the assumption that the earth is a perfect conductor.

The Earth not a Perfect Conductor. — The surface of the earth is, however, not everywhere a good conductor of electricity. The sea and moist soil are better conductors than dry stone. In some places the surface materials of the earth are in fact good insulators.

The attenuation of the electric wave is on this account very different over different parts of the surface of the earth, — conditioned on the fact that there is a greater or less penetration into the insulating portions and a greater or less absorption of energy at the poorly conducting portions. This subject has been submitted to a very remarkable mathematical treatment by Dr. Zenneck. The mathematical reader is referred to Dr. Zenneck's paper[1] or to Professor Fleming's[2] translation and "free paraphrase" of it, for a beautiful discussion of this interesting question. I shall attempt to give here a brief statement of some of Dr. Zenneck's results without attempting to present his reasoning. In doing this I wish to acknowledge the assistance afforded by Professor Fleming's excellent commentary on Zenneck's paper.

In order to simplify the matter, Dr. Zenneck at first considers only the case of a *plane electric wave* traveling without divergence over a flat surface. He is thus at first leaving out of account the spreading out of the wave and the consequent diminution of amplitude by mere distance; and he is also omitting the attenuation of the wave due to the curvature of the surface.

Instead of considering the earth to be a perfect conductor, as has usually been done before, Zenneck looks upon the boundary between the earth and the air as the boundary between two media of different conductivities and different dielectric constants; and he transforms Maxwell's equations so as to take account of the two media.

He arrives at the conclusion that where the earth is a good conductor (for example, *sea water*), the electric force (at the surface) is perpendicular to the surface. For waves of wave length 600 meters, which is the wave length used in most of the calculations, sea water acts as a good conductor, and the electric force at the surface of the sea is perpendicular to the surface, as is shown in

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[1] J. Zenneck: Annalen der Physik, Vol. 23, 1907.

[2] Fleming: Engineering (London), June 4 and 11, 1909.

diagram (*a*), Fig. 91. This figure represents merely how one side of one loop of electric force of our Fig. 90 comes down to the surface. The other side of the loop would likewise be perpendicular to the surface of the sea, but would have an opposite sign.

There would thus arrive at a station at sea a train of electric waves, and the electric force would be *vertical,* and would go through a series of continuous oscillations between positive and negative values, with the frequency of the waves; that is, a train like that of Fig. 92 would come along near the surface in the medium above the surface, and would affect the antenna first in one direction and then in the opposite direction. In the sea water itself beneath the surface, *the forces would be zero.*

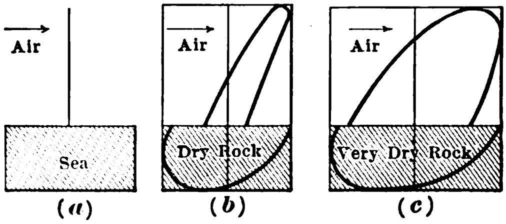

FIG. 91. Diagrams taken from Professor Fleming's paper in the Electrician, illustrating Dr. Zenneck's Theory.

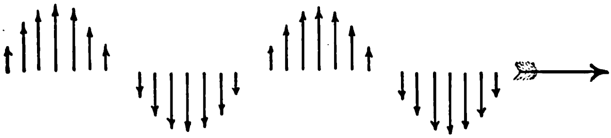

FIG. 92. Diagram of the electric force in a wave train.

Still confining our attention to a wave of wave length 600 meters, let us next suppose the wave to be traveling along a surface of *dry rock* of resistance 100,000 ohms for a meter cube and of dielectric constant $k = 2$ to 3. Zenneck finds for this case that the electric force in the air above the earth is by no means perpendicular, but leans forward in the direction of travel; and that not only the magnitude of the force changes, but the inclination also changes as the wave progresses. There is a similar force, although differently inclined and of different magnitude, below the surface in the rock itself. This condition Zenneck finds to be represented by the semiellipses of (*b*), Fig. 91. The electric force is obtained in magnitude and direction from this diagram (*b*) by considering a radius drawn from the center of the ellipse to a particle moving around the ellipse with the frequency of the wave. The length and the direction of the radius so drawn would represent the changing magnitude and direction of the electric force. Such an electric wave, oscillating both in magnitude and direction is equivalent to two waves, one tending to produce vertical currents and the other tending to produce horizontal currents (the two effects being also out of phase with each other). The horizontal oscillating force induces currents in the earth's surface, and diminishes the energy of the progressing wave, so that in this case the distance to which signals can be sent is less than in the case of the good conductor.

In the case of *propagation over very dry soil,* which is not so good an insulator as the rock (r = 10,000 ohms per meter cube, k = 1 to 3) Zenneck finds the result represented in diagram (*c*), Fig. 91.

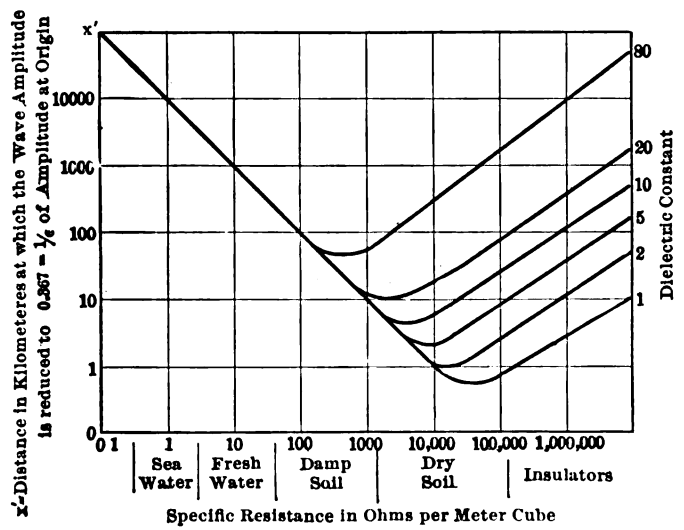

FIG. 93. Curves taken from Professor Fleming's commentary on Zenneck's theory, from the Electrician.

Although the conductivity in this case is between that of (*a*) and (*b*), the form of the ellipses is not intermediate between (*a*) and (*b*). The relation is not a simple one, involving resistance alone; because, in fact, a perfect conductor and a perfect insulator give in the region above the surface the same form of unabsorbed, vertical wave; and there is an intermediate case of conductivity and dielectric constant that gives the most distorted and most absorbed wave. Equations are given by Zenneck for computing any particular case, and he presents the result in the form of a set of interesting curves.

Let us examine first his result for the loss in intensity due to absorption of energy by the surface as the wave travels along over it. For a wave of 600 meters wave length, this is shown in the curves of Fig. 93, which is Zenneck's diagram with added verbal margins by Professor Fleming.

In examining Fig. 93, it should be borne in mind that this diagram takes account of the reduction of intensity by the action of the underlying medium alone, and shows nothing in regard to the law of the diminution of amplitude of the wave by its spreading out in all directions. It is seen from the diagram that except in the case of fairly good conductors, both the resistance and the dielectric constant of the body, over which the wave travels, need to be taken into account and that insulators produce nearly the same attenuation as conductors, and that the worst surface over which to send the waves is dry soil of small dielectric constant. The best surface, so far as concerns absorption alone, is either a good conductor or a good insulator.

But this absorption alone is not all that is to be reckoned with. To get complete information as to the propagation it is necessary to take into account

(1) The effect of the curvature of the earth, and

(2) The effect of the spreading of the wave with the distance (divergence).

Effect of Curvature of Earth. — Although Zenneck's mathematical discussion does not take into account the curvature of the earth, he makes the following important observation in regard to the action of the curvature: " For a good conducting earth's surface with not too small a dielectric constant (for example, sea water) it is highly probable that the curvature of the earth does not materially modify the conditions. Since sea water, for the waves of wireless telegraphy, behaves in all essential points like a metal, it must be assumed that the waves use the sea water surface as guides in the way that waves on wires are guided by the wires of a Lecher system, and like these follow the curvature of the conductor."

For poorly conducting earth, the curvature plays a more detrimental rôle, and for a good insulating surface of small dielectric constant it is certain that the waves would be like those in free space, and would not be constrained at all to follow the curvature of the surface.

From this it is clear that for the easy transmission of the electric waves between stations sufficiently separated to have a large portion of the earth's curved surface between, what is required is a *good conducting and not an insulating* expanse for the waves to travel over. In the succeeding sections we shall compare the distance of transmission over poor conductors with that over a good conducting expanse. To do this we must take into account the divergence of the waves with distance to see whether or not the absorption is important in any particular case.

Diminution of Amplitude by Divergence with Distance. — On account of the divergence of the waves from the sending station, the amplitude of the electric force in the wave is approximately inversely proportional to the distance from the oscillator, provided there is no absorption and provided the distance is not too small. This has been shown theoretically to be true in the case of the propagation of the waves in free space. This law has also been approximately verified for wireless telegraph waves traveling over sea water for distances up to 60 miles, in a very beautiful set of experiments performed on the Irish Channel by Messrs. W. Duddell and J. E. Taylor.[1]

Messrs. Duddell and Taylor's experiments consisted in receiving and measuring the current set up in the antenna of a shore station by electric waves sent out from the British telegraph repair ship *Monarch*, while the ship was at various distances from the receiving station. The very minute currents received were measured by Duddell's thermogalvanometer, of which the following is a brief description:

The thermogalvanometer invented by Mr. W. Duddell[2] is in principle the Radiomicrometer of Professor C. V. Boys, with a modification required to adapt it to measuring oscillatory electric currents instead of heat radiation, for which Boys' instrument was designed. A diagram of the essential parts of the instrument is shown in Fig. 94. Between the poles *NS* of a strong permanent magnet is hung a small loop of one turn of wire *L*, by means of a very fine quartz fiber *F*. The loop is closed below by a thermal junction of bismuth *Bi* and antimony *Sb*. Heat applied in any

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[1] Duddell and Taylor: Journal of the Institution of Electrical Engineers, Vol. 35, pp. 321–352, 1905.

[2] W. Duddell: Phil. Mag., Vol. 8, p. 91, 1904.

way to the thermal junction produces an electric current in the loop, which being in a magnetic field tends to rotate so as to be at right angles to the field. A diminutive mirror *M* fastened to a vertical glass rod at the top of the loop and rotating with the loop permits the deflections of the loop to be read by means of a telescope and scale. This part of the apparatus is the radiomicrometer of Professor Boys, and was used by Boys to measure small quantities of radiant heat, which was allowed to fall on the thermal junction. Professor Boys estimated that with a lens 18 inches in diameter for concentrating the radiant heat upon the thermal junction, he could measure the heat received from a candle three miles away. Mr. Duddell's very ingenious modification of this delicate instrument so as to adapt it to the measurement of oscillatory electric currents, consisted in placing, in the case of the suspended system and very near to the thermal junction, a "heater" of fine wire, as shown in the figure. Electric oscillations conducted through this "heater" heated it, and a part of the heat so produced was communicated by radiation and convection to the suspended thermal junction. By the use of a set of interchangeable heaters the instrument could be given a wide range of sensitiveness.

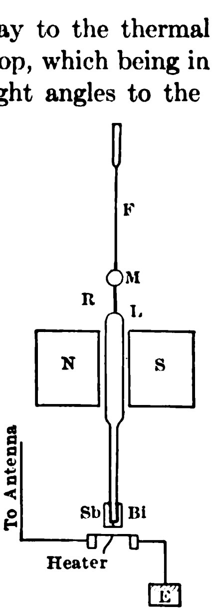

FIG. 94. Duddell thermogalvanometer.

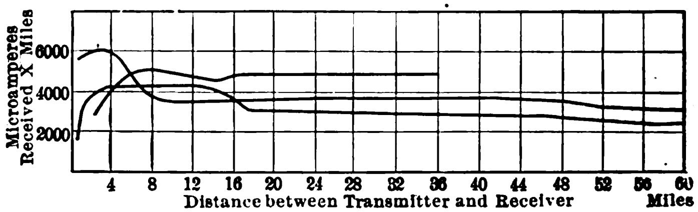

FIG. 95. Results of Messrs. Duddell and Taylor's experiments on distance law.

Using this thermogalvanometer for measuring the received current Messrs. Duddell and Taylor found that within certain limits the current received is approximately inversely proportional to the distance from the sending station; that is to say, the current multiplied by the distance is approximately constant. Figure 95 shows graphically the results obtained during three cruises of the

Monarch. In these curves the product of received current times distance is plotted against the distance. If this product were a constant, the curves should each be a straight line parallel to the horizontal axis. It is seen that between 16 and 60 miles each of the three curves is approximately horizontal. Messrs. Duddell and Taylor's measurements will therefore be seen to show that the received current from a given constant sending station is somewhat nearly inversely proportional to the distance. In view of the great difficulty of keeping the conditions at the sending station constant throughout each of the experiments, and in view of the difficulty of measuring the small currents received, Messrs. Duddell and Taylor deserve much praise for this laborious and

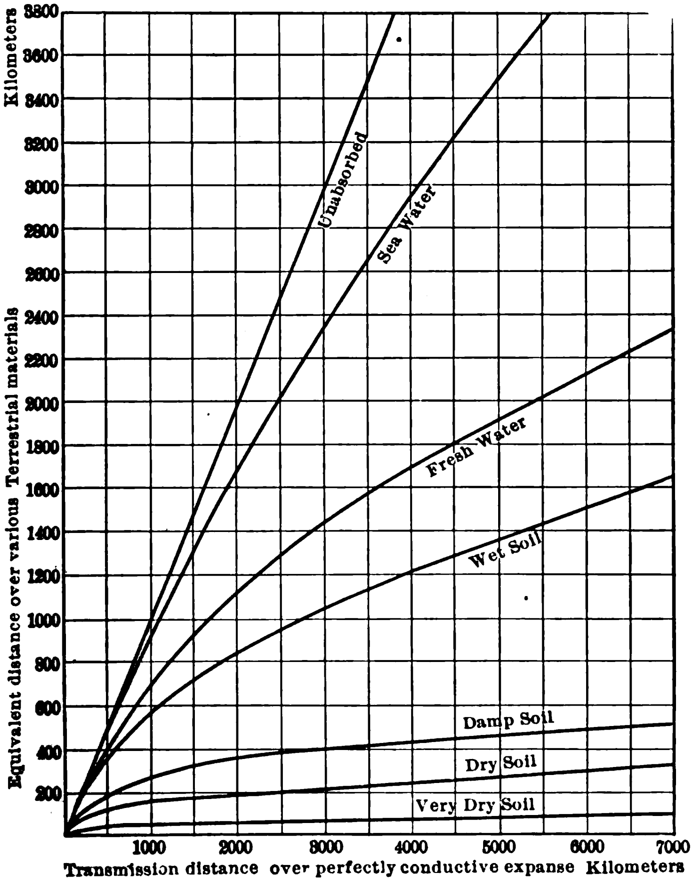

FIG. 96. Comparison of transmission distances.

careful piece of work, which was performed at a time when quantitative experiments in wireless telegraphy were few.

Diminution of Amplitude by Divergence Together with Absorption. — Assuming the inverse first-power law to represent the effect of divergence, let us now combine with this effect the effect of absorption of the waves in passing over various terrestrial surfaces. To do this we shall make use of Zenneck's theoretical treatment of the question of absorption. Following Zenneck's equations and data, I have constructed the chart of Fig. 96, showing the equivalent distance of transmission over various terrestrial materials in comparison with the transmission distance over a nonabsorbing good-conducting surface. The wave length assumed in this calculation is 600 meters. The results shown by the curves of Fig. 96 are also presented numerically in the following table:

TABLE I.

GIVING EQUIVALENT DISTANCES OF TRANSMISSION OVER VARIOUS TERRESTRIAL MATERIALS. FROM ZENNECK'S EQUATIONS AND DATA. WAVE LENGTH 600 METERS. THE DISTANCES ARE IN KILOMETERS.

Equivalent Distances of Transmission over						
A Perfectly Conductive Expanse	Sea Water.	Fresh Water or Very Wet Soil.	Wet Soil.	Damp Soil.	Dry Soil.	Very Dry Soil.
100	99	98	97	80	70	30
200	195	170	165	115	85	35
300	290	260	215	140	105	40
400	385	350	295	170	120	43
500	480	400	340	190	130	48
1000	920	700	560	270	150	55
1500	1320	940	720	320	175	60
2000	1680	1140	850	360	185	63
2500	2030	1300	950	380	200	68
3000	2360	1450	1050	400	215	70
3500	2680	1580	1140	420	225	75
4000	2970	1700	1220	430	240	80
4500	3230	1820	1300	440	255	82
5000	3490	1915	1370	460	270	85
5500	3750	2040	1440	475	280	87
6000	3960	2140	1520	495	295	90
6500	4200	2240	1580	500	310	92
7000	4450	2340	1640	520	320	95

From this table it will be seen that the effects of absorption show up more and more with increasing distance of transmission. As an example of the meaning of the table, take the case where 3000 stands in the first column. The table shows that a station that could send waves capable of being read at a distance of 3000 kilometers over a perfectly conductive expanse could be read at a distance of 2360 kilometers over the sea; 1450 kilometers over fresh water or a rain-soaked soil; 400 kilometers over damp soil, and only 70 kilometers over some kinds of very dry soil. Although exact quantitative experiments are lacking in regard to the equivalence of these various distances in a practical case, yet these figures do not seem to be very different from the reports of wireless telegraph engineers as to the comparative ease of attaining great distances over sea and over various kinds of land.[1]

A deduction of the numerical results shown in the above table by straightforward reasoning from Maxwell's theory of electric waves, and the agreement of these results with the facts of experience, ought to be sufficient to satisfy us that we are dealing with true Maxwellian electric waves and not with some new kind of electrical manifestation, as some writers have occasionally intimated.

Absorption Conditioned on Wave Lengths. — In discussing Zenneck's results we have confined our attention to a wave length of 600 meters. Zenneck has, however, shown how to modify his formulas in order to apply them to other wave lengths; and Professor Fleming has carried the calculations through for several other wave lengths, and draws the following conclusions:

"1. In the case of transmission over sea, the absorption for waves of 300 meters wave length is not very large; but, nevertheless, increasing the wave length to 3000 meters is an advantage.

2. In transmission over land the absorption of waves 300 meters long is very sensible, and increasing the wave length to 3000 meters produces a very beneficial effect.

3. In the case of extremely dry soil the terrestrial absorption is very large, and increasing the wave length from 300 meters to 3000 meters produces no marked improvement."

Effect of Bodies of Water below the Earth's Surface. — For information on this subject the mathematical reader is referred to an article by Dr. F. Hack, *Annalen der Physik*, Vol. 27, p. 43, 1908.

The Effect of Light and Darkness on Transmission. — Another important subject connected with the long distance transmission of wireless telegraph signals is the effect of light and darkness on transmission distance. In experiments conducted between

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[1] See on this subject, Capt. H. B. Jackson, R.N., F.R.S., "On Some Phenomena affecting the Transmission of Electric Waves over the Surface of Sea and Earth," Proc. Roy. Soc. London, 1902, Vol. 70, p. 254. Also Fleming, The Principles of Elec. Wave Telegraphy, 1906, p. 606.

Poldu and the steamer *Philadelphia* in March, 1902, Mr. Marconi found that the messages could be received at much greater distances at night than in the daytime. Messages that could be received at a distance of 1600 miles at night could be received only at a distance of 700 miles in the daytime. This difference between the distance of transmission in darkness and in daylight is now a matter of common experience in wireless telegraphy. The difference does not manifest itself at short distances. Messrs. Duddell and Taylor, in their classical experiments above described, could not find any difference between the intensity of signals received at night and those received by day, when the distance between the sending station and the receiving station was 60 miles over sea. At distances of 150 miles the difference is distinctly noticeable, and for greater distances the difference between night and day transmission is correspondingly greater. Recently Mr. Marconi has pointed out that the difficulties of transmission to long distances are especially marked at dawn and at sunset.

Pickard's Experiments on Effect of Light and Darkness. — In January and July, 1909, Mr. Greenleaf Whittier Pickard made some quantitative experiments on this subject, and he has very kindly given me permission to use his data, although they have not as yet been published by him elsewhere. For the purposes of these experiments Mr. Pickard utilized the signals sent out from the Marconi station at Glace Bay, in the course of their regular transatlantic wireless telegraph experiments, and he measured the relative strength of the signals received at Amesbury, Massachusetts, at different hours of the day and night. The distance between Glace Bay and the receiving station at Amesbury is about 600 miles. Mr Pickard had to take his observations at any time when the Glace Bay station was in action, and since he had no control over the activities of this station, it was necessary to combine observations extending over two or three days in order to cover fairly well the whole of the 24 hours.

A set of the observations taken by Mr. Pickard in the month of July, 1909, is plotted in Figure 97. In this diagram the hour of the day or night is plotted horizontally. The values plotted vertically, which I have called *relative intensity of received signals*, are values obtained by the use of a crystal detector consisting of a crystal of bornite in contact with a crystal of zincite. Such a high-resistance crystal contact acts as a rectifier of the oscillatory currents generated in the antenna by the incoming waves, so that these high-frequency currents are given a unidirectional character and may be measured on a galvanometer by reading its deflections, or they may also be measured on a telephone receiver by determining what shunt is necessary about the telephone to reduce its sound to inaudibility. The telephone method is the more convenient and this was usually employed by Pickard, who, however, reduced his observations to galvanometer readings by calibration and by control experiments. The *relative intensities of received signals*, plotted in the diagrams, are the rectified currents produced by the electric waves in terms of that rectified current which will produce just audible sounds in the telephone.

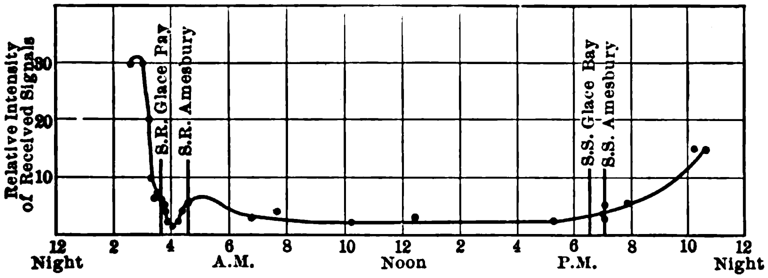

FIG. 97. Observations taken by Mr. Pickard on the relative intensity of signals received at different hours of day and night.

We have not yet had a discussion of these crystal rectifiers as used to detect or measure electric waves, but it should be said in passing that on account of the characteristics of these detectors the relative intensities here plotted are not proportional to the energy or to the alternating current generated by the received signals. We must therefore look upon the intensity values of Mr. Pickard's curves as conditioned by the form of detector used. Since, however, the detector employed was one of high sensitiveness and one much used in commercial wireless telegraphy, these curves obtained under actual working conditions are highly instructive. As a precaution against changes that might occur in the detector, Mr. Pickard repeatedly tested the detector by throwing it into a circuit containing a constant small alternating electromotive force and a galvanometer, and when necessary the detector was readjusted so as to give a fixed rectified current under the fixed e.m.f.

By a reference to the curves of Fig. 97 we see that for the particular crystal detector, used with a 2000-ohm telephone receiver as in actual practice, there was obtained in the telephone receiver about 30 times as much current near midnight as during the daytime.

The wave length of the Glace Bay station, from which the signals originated, was 4000 meters; so that in spite of the fact that the use of such great wave lengths has been reported to diminish the discrepancy between night and day transmission, Mr. Pickard's measurements show that there still remains a great weakness of the daytime signals as compared with signals transmitted at night.

Mr. Pickard has called my attention to the very striking depression in the intensity curve at dawn. This depression occurs between the time of sunrise at Glace Bay and the time of sunrise at Amesbury (3.40 and 4.31 A. M. respectively on July 28, both reduced to Eastern Standard Time [1]). Mr. Pickard says: "Although this effect is small, it is too large to be accounted for by observational errors even in a single series, and, as a matter of fact, I find it running through all my dawn measurements, — about a dozen, all told." (Quotation from a letter of Mr. Pickard.) This is in agreement with Marconi's observation in regard to the difficulty of signaling at dawn. A similar depression was not found by Pickard at sunset, possibly, he thinks, on account of a paucity of observations at sunset due to the fact that the Glace Bay station was seldom operating at sunset.

It is very noticeable that the daylight absorption persists for some time after sunset and begins some time before sunrise. Whence it appears that, in summer at least, the best working between the two stations examined in the experiment lasts for but a few hours each night; perhaps about four hours. This time of good working ought to be somewhat longer for two stations having the same hour of sunrise and sunset. On the other hand, in the case of two transatlantic stations which are situated nearly east and west of each other, and which have a difference of time of about 5 hours, if the weakening of the signals begins before sunrise at the eastern station and continues after sunset at the western station, the communication would be at its best between the two stations for only a very short time, perhaps two or three hours each night, particularly in summer. Thus we see that in the case of wireless telegraphy, in addition to a commercial reason, there is also a physical reason for "night messages at reduced rates."

Efforts to Explain Action of Daylight. — When the inequalities

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[1] For an accurate computation of the time of sunrise and sunset of the Amesbury and the Glace Bay stations I am indebted to Professor Robert W. Willson, Professor of Astronomy at Harvard University.

of day and night transmission of electric waves were first observed, the theory was at once advanced that the effect was due to the action of the daylight in rendering the air conductive for electricity. We have noticed in Chapter II that light, especially ultraviolet light, is one of those agencies that ionizes the air by breaking it up into charged positive and negative particles, and that air so ionized will conduct electricity in a manner known as convection; that is, if the ionized air is brought between two plates which are charged to different potential, the positively charged particles in the ionized air will be driven from the plate of higher potential to the plate of lower potential, while the negatively charged particles will be driven in the opposite direction. This motion of the charged particles constitutes an electric current flowing between the plates.

Inadequacy of Explanation Based on Conductivity of Air Near the Surface of the Earth. — This suggests two ways in which the effect of the light would act to decrease the distance of transmission by daylight, assuming that the air near the earth is more conductive in the daytime than at night.

(1) The conductivity of the air in the daytime in the neighborhood of the sending antenna would cause the charge to leak off the antenna so that it would not be charged to so high a potential and would therefore not produce so large an oscillating current as at night.

(2) The air in the interval between the sending and the receiving station, being more conductive in the daytime, would absorb more of the energy of the waves than at night.

Both of these explanations, based on the conduction of the air near the earth, seem entirely inadequate to explain the phenomenon. The first explanation is untenable because the effects of the daylight do not manifest themselves when the stations are separated by short distances, and can, therefore, not be localized at the sending station. As to the effect of absorption, if we take the average experimentally determined value for the conductivity of the air near the surface of the earth as 2×10^{-25} electromagnetic units for a centimeter cube of air,[1] and substitute this value in the formula[2]

$$A = A_0 e^{-\xi x},$$

where for small conductivity

$$\xi = 2 \pi \sigma \times 3 \times 10^{10};$$

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[1] This value is taken, following Zenneck, from Gerdien, **Physikalische Zeitschrift,** Vol. 6, p. 647, 1905.

[2] This formula is derived in Boltzmann's Vorlesungen ueber Maxwells Theorie, § 96 (Leipzig, 1891).

in which A_0 is the amplitude if there were no absorption, A the amplitude of the absorbed wave, x the distance in centimeters, σ the conductivity in e. m. u., we arrive at the result that the absorption due to the conductivity of the air is entirely negligible, even for very large distances. In order that the absorption of the air should reduce the amplitude of the wave to one-third its value in 3000 kilometers distance the conductivity of the air would have to be 100,000 times as great as it really is.

We therefore cannot look upon the attenuation of the electric waves in daylight as due to a periodic variation of the conductivity of the air in the regions near the earth's surface, because these variations of conductivity, according to measurements that have been made of this quantity, are entirely too small.

It is also interesting to note that the fluctuations of the conductivity of the air from maxima to minima do not coincide in time with the fluctuations of intensity of transmitted waves. The average daily variation of the conductivity of the air as determined by Zoelss from 2864 observations extending over two years is shown in the curves of Fig. 98. These curves were obtained by determining the rate of leak of a charged body. The curves $a+$ and $a-$ were obtained when the body was charged positive or negative respectively. Curves of this character, although they differ at different places on the earth, usually show a minimum dissipation of electric charge at sunrise and a little after sunset, a maximum near noon, and a second maximum near midnight. This would correspond to good transmission at sunrise and sunset and poor transmission at noon and at midnight, which does not accord with the facts.

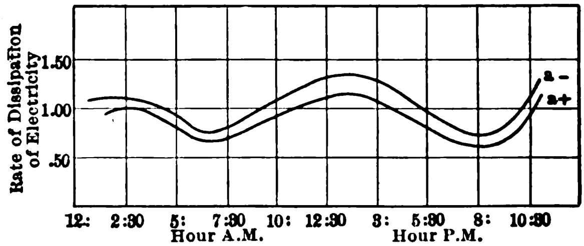

FIG. 98. Rate of dissipation of electricity at different hours of day and night (Zoelss).

Effect of Ionization of Upper Strata. — The action of the sun's light in ionizing the air ought to be much greater in the upper regions of the atmosphere than at the surface of the earth, because the chief ionizing rays of light are those of very short wave length (the ultraviolet), and these short waves of light are strongly absorbed by the air, and therefore do not penetrate to a very great depth in the earth's atmosphere. The stratum of upper atmosphere, rendered conductive by the sunlight, may serve to some extent as a reflector of the electric waves so as to assist in confining the waves to the surface of the earth. If this effect were appreciable, the waves would be more strongly confined to the surface of the earth in the daytime than in the night, and transmission would be easier in the daytime than at night, except for a possible interference between the direct and the reflected wave. This interference, if it should exist, would intensify waves of some wave lengths and partially annul waves of a different wave length, so that by changing the wave length through a range corresponding to a half period it ought to be possible to turn the interference to advantage. No such effects have been found, and the increase of the conductivity of the upper air by ionization in daylight when looked upon as a reflector does not act in the proper direction to be the determining factor in explaining the inequality of transmission of electric waves by day and by night. Professor A. E. Kennelly has called my attention to the fact, however, that there may exist in the upper strata, as we pass upward, a gradual change from insulating to good conducting strata, which, coupled with irregularly distributed conducting areas, might result in a general deflection upward of the waves, and a consequent loss of received energy, and that this effect might be greater in daylight than at night. This theory has not yet been given exact mathematical expression, so that up to the present we seem not to have found an adequate explanation of the difficulties of daytime transmission in comparison with night transmission of electric waves to great distances. The question is one of great importance from a theoretical standpoint, and if the discovery of the explanation of the phenomenon should bring with it the discovery of a means for bringing the distance of communication by daytime up to that by night, it would remove a very exasperating limitation to electric wave telegraphy.

Experiments with the use of very long electric waves are under way by the National Electric Signaling Company and by the Marconi Company, and it is reported that some approach toward uniformity of day and night transmission has been made.

CHAPTER XVI

ON DETECTORS

Having examined at some length various problems in connection with the propagation of electric waves to great distances over the surface of the earth, let us take up next a description and examination of some of the instruments used in receiving the oscillations of wireless telegraphy and translating them into audible or visible signals.

The instruments employed are the *indicating instrument* (relay, galvanometer, telephone, etc.), by which the signals are read, and the *detector*, by which the high-frequency oscillations are put into a condition to affect the indicating instrument.

INDICATING INSTRUMENTS

Classification of Indicating Instruments. — The indicating instrument now usually employed is (1) a sensitive telephone receiver, but (2) a relay, in connection with a sounder or ordinary telegraphic recording instrument, (3) a galvanometer, or (4) an electrometer, may serve as indicating instrument.

Sensitiveness of Relay. — The most sensitive relay will trip with about one one-thousandth of a volt e.m.f. applied to its terminals. With the restoring spring of the instrument set under sufficient tension to act reliably and rapidly enough to receive messages, a relay (even when constructed to have high sensitiveness) would require perhaps one two-hundredth of a volt to operate it.

Sensitiveness of Telephone Receiver. — Dr. L. W. Austin [1] has recently made some experiments on the volt sensitiveness of a pair of 800-ohm Schmidt-Wilkes head telephone receivers, such as have been very much employed in recent electric-wave telegraphy. In stating the sensitiveness of a telephone receiver it is necessary to specify the frequency, because the sensitiveness depends very markedly on the frequency of the e.m.f. applied to the circuit. This is no doubt largely due to the possession by the diaphragm

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[1] Bulletin of the Bureau of Standards, Vol. 5, p. 149, 1908.

of a natural period of vibration. The following table (Table II) taken from Dr. Austin's paper gives the number of volts required to produce just audible sounds in the pair of telephone receivers under the application of sinusoidal electromotive forces of various numbers of complete cycles per second.

TABLE II.

VOLT SENSITIVENESS OF A PAIR OF SCHMIDT-WILKES 800-OHM TELEPHONES.

No. of cycles per second.	Volts to produce audible sound.
60	620 millionths of a volt.
120	290 " " "
180	170 " " "
300	60 " " "
420	17 " " "
540	8 " " "
660	3 " " "
780	1.1 " " "
900	0.6 " " "

Sensitiveness of Galvanometers. — A very sensitive galvanometer of ordinary construction and of about 1000-ohms resistance will give a visible deflection with less than one ten-millionth of a volt, but such an instrument has too slow a period (ten seconds) to use in indicating wireless telegraph messages. In 1903 Professor Einthoven[1] designed a new form of galvanometer that has a very rapid period and at the same time a high sensitiveness. Einthoven's instrument consists of a very fine silvered or platinized quartz fiber hung between the poles of a strong magnet. The current to be measured is sent through the silver or the platinum coating on the fiber, and the fiber tends to move out of the magnetic field. The deflections of this fiber may be observed with a microscope, or may be photographed on a rotating drum carrying a photographic film. The direction of the deflection of this galvanometer, like that of the ordinary galvanometers, reverses with reversal of the current. In one one-hundredth of a second Einthoven's instrument will give a deflection sufficiently large to be registered on the photographic plate, under application of an e.m.f. of one ten-thousandth of a volt. Used in connection with a suitable

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[1] Annalen der Physik, Vol. 12, p. 1059, 1903.

detector it is, therefore, adapted to the photographic registration of wireless telegraph messages, and has been employed for this purpose.

Sensitiveness of the Capillary Electrometer. — A very minute column of mercury in a capillary glass tube and in contact with sulphuric acid is employed in the construction of a capillary electrometer. Under the action of a current, the electrolytic polarization of the contact causes a change of the surface tension of the mercury and causes the column of mercury to rise or fall in the glass tube. This minute motion of the mercury column is observed with a low-power microscope. A delicate capillary electrometer will give a readable deflection with an applied electromotive force of one ten-thousandth of a volt, and is capable of use as an indicating instrument.

In what follows I shall describe the method of employing some of these indicators in connection with detectors for rapid oscillations.

Why a Detector in Addition to the Indicating Instruments Must be Employed. — Some misconception exists as to why a detector must be employed with these various indicating instruments in order to receive and read the messages. The misconception is that the detectors are more sensitive to electrical energy than the telephone receiver or galvanometer is. This is not the case. But in the reception of the electric waves the electrical energy received, being in the form of rapid oscillations, cannot affect the telephone or the galvanometer. These rapid oscillations cannot affect the galvanometer because the deflections of the galvanometer reverse with reversals of the current, so that the deflecting impulses, if applied directly to the galvanometer, would be first in one direction and then in the other, with a frequency of the order of a millionth of a second, and motion of a mass as light even as the fiber of the Einthoven galvanometer could not result from these rapidly reversing impulses. Likewise, a telephone diaphragm could not be made to move with such rapidity. In the case of the telephone, on account of the large self-inductance of the instrument, the high-frequency e.m.f. generated by the waves would produce in a circuit containing a telephone receiver only extremely weak currents.

The use of the detectors is to transform these rapid oscillations into effects that can be manifested by the indicating instruments. How this transformation is accomplished will be explained in the subsequent discussion.

CLASSIFICATION OF DETECTORS

We shall describe the detectors under the following more or less arbitrary titles:

- Coherers.
- Magnetic Detectors.
- Thermal Detectors.
- Crystal Rectifiers.
- Electrolytic Detectors.
- Vacuum Detectors.

In illustrating the manner of introducing these various detectors into the receiving system a diagram of only a simple form of receiving circuit will be exhibited with the descriptions. It is to be understood, however, that all the detectors can also be used in various forms of direct and inductively connected circuits as well as in the simple circuits.

COHERERS

As coherers, we shall include only those detectors which employ a loose contact and require to be shaken, tapped, or otherwise moved to restore the contact to its sensitive condition after the receipt of a signal. We have already described the filings-tube coherer of Branly and Marconi. A great many modifications of this instrument have been made, including the use of a single contact or a few contacts in series or parallel, between metallic balls or points, to take the place of the filings. Also a great many variations in the method of decohering the contacts have been made. These will not be described here.

These various forms of coherer have their importance in the fact that, on the receipt of electric waves, a sufficiently large current is started in the local circuit to operate a relay, ring a bell, or give other form of alarm that can be heard at a distance from the operator's desk. Also the current permitted to flow in the local circuit of the coherers during the receipt of electric waves is sufficiently large to start machinery and control a mechanism (for example, a torpedo or dirigible craft) at a distance. This kind of result is not easily attained with the other form of detectors listed above, which do not permit of the use of sufficiently large currents in the local circuit to sound an alarm or start electrical machinery.

Thus the coherer, though lacking in sensitiveness to feeble waves and not now generally employed in the receipt of messages, has still a field of usefulness.

Besides the filings coherer described in Chapter XII, we shall describe here another interesting form of coherer,— that devised in 1902 by Lodge, Muirhead and Robinson.

The Lodge-Muirhead Coherer. — This instrument consists of a small steel disc *A* (Fig. 99), rotated by a clockwork, so that the disc is just separated from a column of mercury *B* by a thin film of mineral oil on the surface of the mercury. One electrical connection is made to the wheel through a brush *E*, the other connection is made to the mercury well through the binding post *H*.

The impulse of the electric oscillations breaks down the oil film and establishes momentary cohesion between the steel disc and the mercury. A current from a local battery passes through the disc and mercury contact, and operates a siphon recorder, which is used in series with the battery and the coherer. After the impulse ceases the motion of the disc brings continuously a fresh oil film into the contact and causes decoherence. The siphon recorder gives a written record of the dots and dashes of the message. A felt brush at *K* serves to keep the rotating disc free from dust before and after contact with the mercury.

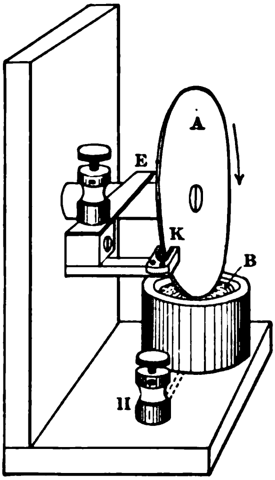

Fig. 99. The Lodge-Muirhead-Robinson coherer.

Concerning the Theoretical Explanation of the Action of the Coherers. — A generally accepted theory as to the reason for the coherence of the filings, or other form of imperfect contact used in the coherers, has not been established. I shall state briefly some of the views presented in explanation of the phenomenon. Before the arrival of the waves, the high resistance of the contact is generally supposed to be due to the presence of some kind of poorly conductive film at the contact. In the case of the Lodge-Muirhead coherer, the insulating film is evidently present in the form of a film of oil. In many of the other coherers a poorly conductive film is present in the form of an oxide of the metal.

This is evident from the fact that in some cases the metallic particles (e.g., iron or steel) are artificially prepared by oxidizing them in order to make of them a good coherer. The poorly conductive film may also be present in some cases in the form of a sulphide of the metal. On account of the readiness with which many metals (called the " baser metals ") enter into combination with the oxygen or sulphur dioxide of the air, a thin film of oxide or sulphide is always present on the surface of most of the baser metals, unless special care is taken to remove it.

Apart, however, from the existence of such films of foreign matter at the contact, it seems not impossible that the high resistance before the arrival of the waves may be a property of the surfaces of even pure metals when these surfaces touch only very lightly.

If we assume the presence of the poorly conductive film at the contacts of the coherer, we may suppose that, on the arrival of the electric waves, the poorly conductive film is removed by the heat developed by the oscillatory currents. This starts the local current, which, developing further heat, still further improves the contact and permits the passage of further current. Instead of heat being the chief agency in removing the oxide or other poorly conductive film, or in bringing together the loose contacts, it may be that this is done by the electric attraction between the filings, which before the current starts will be charged with opposite signs of electricity, and which under the added e.m.f. produced by the electric oscillations may attract each other strongly enough to pull the contacts together.

We shall learn more about the electrical properties of high resistance contacts when we come to the study of *crystal rectifiers*. It is therefore proposed to omit further discussion of the specific action of the coherers, because of the more general character of the information to be presented later.

In the meanwhile some of the other detectors which do not depend on the properties of a loose contact are discussed.

MAGNETIC DETECTORS

Rutherford's Magnetic Detector. — In 1895 and 1896 Professor E. Rutherford[1] discovered a sensitive method of detecting electric waves by causing the electric oscillations set up by the

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[1] E. Rutherford, "A Magnetic Detector of Electrical Waves and Some of Its Applications." Phil. Trans. Roy. Soc. London, 1897, Vol. 189, A., p.1; also Proc. Roy. Soc. London, 1896, Vol. 60, p. 184.

waves to demagnetize a bundle of fine steel wires. This bundle of steel wires consisted of about twenty pieces, each 1 cm. long and .007 cm. in diameter. The individual wires were insulated from one another by shellac varnish, and the bundle was placed within a small coil of about 80 turns of insulated copper wire. The bundle of steel wires was magnetized by the use of a magnet, and was then brought up near a magnetometer, consisting of a small compass needle suspended by a fine fiber and carrying a small mirror by which its deflections could be read. The needle of the magnetometer was deflected by the magnetized bundle of steel wires. If now electric oscillations were passed through the coil surrounding the bundle of steel wires, these wires lost some of their magnetism, which was shown by a diminished deflection of the neighboring magnetometer. Rutherford found that by connecting the coil around the wire bundle to a resonator, electric waves from a small Hertz oscillator placed at a distance of a half mile across the city (Cambridge, England) could be detected. With this instrument Rutherford performed many interesting experiments and carried out an important research on the damping of electric oscillations.

Marconi's Continuous Band Magnetic Detector. — In 1902 Marconi devised two other forms of magnetic detector, one of which has met with extensive use in practical wireless telegraphy, and is here described. Reference is made to Fig. 100. A band made up of a bundle of fine, hard-drawn iron wires, insulated from one another to prevent eddy currents, is carried on the periphery of two wooden discs, one of which is turned by a clockwork or a motor, so that the band moves at the rate of 7 or 8 cm. per second. This endless band of iron wire passes axially through a small glass tube *g*, around which two coils are wound. One of these coils, *b*, is connected into the oscillation circuit. In the example shown, the receiving circuit is of the simple type consisting of antenna, detector and ground. In this case the coil *b* is put directly into the antenna circuit, so that electric oscillations from the antenna, *A*, pass through this coil of the detector. We shall call the coil *b* the *oscillation coil* of the detector. Around the oscillation coil is a second coil, *C*, connected in series with a telephone receiver.

To produce a state of magnetization in the moving band, two permanent horseshoe magnets are placed near it. Two like poles, *NN*, of the magnets are placed above the center of the oscillation coil, and the other two poles, *SS*, are placed near the band where it approaches and leaves the coils. These magnets induce magnetic *poles* in the moving band. One of these induced poles, say the South pole, is within the coils, and the two other consequent poles (North poles in our illustration) are near the point where the band enters and leaves the coils.

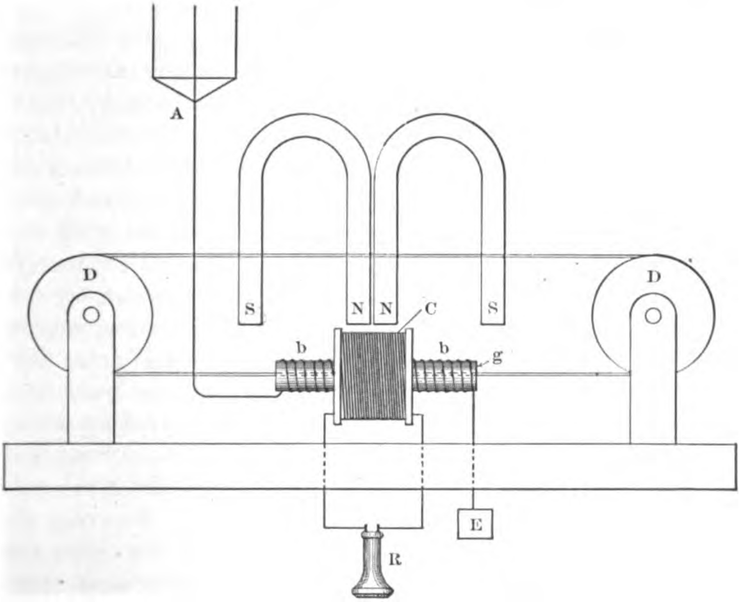

FIG. 100. Marconi magnetic detector.

General Facts in Regard to the Explanation of the Action of the Marconi Magnetic Detector. — If we confine our attention to a point on the moving band, it is seen that, as the band moves forward, this point becomes a North pole outside the coils, changes to a South pole within the coils, and becomes again a North pole after issuing from the coils. There is, however, within the coils, *a steady state of magnetization*, for although the band is in motion, every particle of the band, as it passes a particular point within the coils, comes to a particular state of magnetization, so that the magnetic condition is fixed with respect to the magnetizing magnets. This gives a steady state of magnetization within the coils and produces no inductive effect in the form of currents in the telephone circuit.

If now a train of electric oscillations passes through the oscillation coil *b*, the magnetization of the part of the band within the coil is changed, and this change of the magnetization produces a transient current in the coil *C*, and the telephone gives a click. A whole series of trains of electric oscillations gives a series of clicks, producing a musical note with a pitch depending on the frequency of arrival of the trains; and this is the frequency of the sparks at the sending station. So that one hears, when listening into the telephone attached to the magnetic detector, a sound like that produced by the spark at the sending station. The pitch of this sound is determined by the period of the vibrator of the sending induction coil; or, in case an alternating current transformer is used to charge the sending antenna, the fundamental pitch of the spark, and consequently the note that one hears at the receiving station, is determined by the number of reversals per second of the alternating current supply at the sending station, although other notes may be superposed on this fundamental note, due to the fact that with some adjustments more than one spark at the sending station occurs at each reversal of the alternating source.

We shall now discuss the nature of the change occurring in the magnetization of the iron band of the detector under the action of the oscillations set up by the incoming waves. The very rapid oscillations produced by the electric waves used in wireless telegraphy cannot produce a sound in a telephone either when applied to it directly or inductively, because, on account of the self-inductance that is necessary to the telephone, these very rapid oscillatory currents cannot traverse its circuit. If they could traverse its circuit, the diaphragm of the telephone could not take up such rapid vibrations, and if it did we could not hear them, for the highest note audible to the human ear makes only 35,000 vibrations per second. Our wireless telegraph detectors must be so constructed that the rapid oscillations of a train of waves act *integratively* upon it, so that the *train* produces a single response in the telephone; and a series of trains produce a series of responses. This series of responses we can hear in the telephone, because the series of trains of waves follow each other with a periodicity that is audible.

In regard to the manner in which a train of oscillations act integratively upon the magnetized moving iron band of Marconi's form of the magnetic detector, I shall present a few paragraphs of explanation.

Explanation Assuming a Suppression of Hysteresis by the Oscillations. — Many experiments have been made in the effort to discover just what is the effect produced on the magnetization of the bundle of iron wires by the oscillations within the coil surrounding the bundle. A steady current in the coil would magnetize the iron wires of the bundle. An oscillatory current, according to the experiments of C. Maurain,[1] *produces a suppression of hysteresis in the iron.*

In explanation of the term "hysteresis," reference is made to Fig. 101, in which *magnetizing force* is plotted horizontally and the *magnetization* produced by it is plotted vertically. This curve represents the *hysteresis* in a specimen of hard-drawn iron wire such as is used in the magnetic detectors. If we start with the magnetizing force equal zero, and increase it to *OL*, the magnetization follows the curve *OA*. If now we reduce the magnetizing force gradually to zero, the magnetization follows the curve *AC*. That is, the state of magnetization produced by the magnetizing force when it is decreasing is not the same as the state of magnetization produced by the force when it is increasing, and after the force is removed, some magnetization represented by *OC* is left in the specimen. In order to reduce this magnetization to zero, it is necessary to apply a reversed magnetizing force *OD*. If we go on increasing the reversed magnetizing force to *OM*, the magnetization follows the branch *DE* of the curve. On decreasing and again reversing the force, the magnetization traces out the branch *EFGA*. The complete diagram is called a *hysteresis cycle.*

Hysteresis is the property of iron, steel and other magnetizable metals characterized by the fact that the change in magnetization due to the application of a magnetizing force depends on the previous state of magnetization of the specimen. The state of magnetization assumed by a specimen when the magnetizing force is gradually removed is not the same as the state of magnetization assumed by the specimen when the force is gradually applied. The magnetization produced by a given magnetizing force is not completely annulled by withdrawing the magnetizing force. The hysteresis effect is small in very soft iron, is increased by hardening the iron, and is very great in glass-hard steel.

According to the experiments of C. Maurain, which we are now discussing in their application to the magnetic detector, the superposition of a sufficiently strong oscillatory magnetizing force upon a slowly varying magnetizing force causes a suppression of the hysteresis in the specimen. If the oscillatory force is weak, the

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[1] C. Maurain, Comptes Rendus, Vol. 137, p. 914–916, 1903.

suppression is only partial, giving for the specimen characterized in Fig. 101 a diminished hysteresis, such as is represented in Fig. 102.

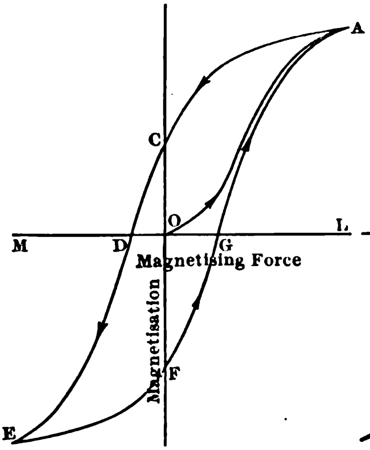

FIG. 101. Hysteresis curve.

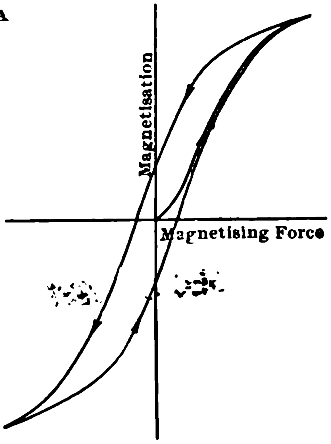

FIG. 102. Hysteresis curve.

In terms of this result we have a possible explanation of the magnetic detector. Reference is made to Fig. 103. With the poles

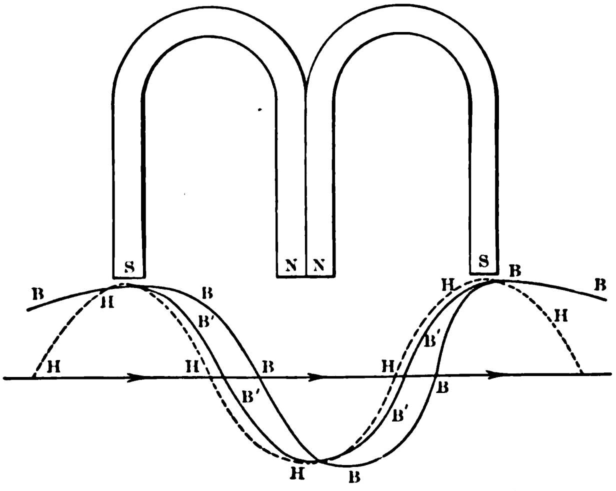

FIG. 103. Diagram in explanation of Marconi magnetic detector.

of the permanent magnet in the positions *SNNS*, the magnetizing force acting on the band will be positive under the

South poles and negative under the North poles; and following our usual method of plotting, the magnetizing force can be represented approximately by the *dotted wavy curve* H of Fig. 103. Now if we suppose the band to be moving in the direction of the arrows, the North magnetization under the first South pole will not follow the curve of force, but will *persist*, and follow approximately the continuous curve B. If now oscillations produced by the electric waves are allowed to flow around the oscillation coil, the hysteresis in the band is suppressed, so that the curve of magnetization B falls back into the position B', which is nearer the curve of magnetizing force H of Fig. 103. This change from the condition B to B^1 is equivalent to a motion toward the left of the magnetic distribution in the coil, and therefore induces a current in the coil containing the telephone in circuit. When the waves cease, the state of magnetization returns to that represented by the curve B. We have thus with each train of waves a back and forth shift of magnetization of the band, and consequently a to and fro motion of the telephone diaphragm.

While this description of the process seems a very reasonable explanation of the action of the detector, yet, for the benefit of those readers who may wish a little more insight into the processes occurring in iron or steel submitted to an oscillatory field, I beg leave to present a brief account of some experiments by E. Madelung, in which he made direct observations of the effect of electric oscillation on the magnetization of iron and steel.

Experiments of E. Madelung. — A very comprehensive and beautiful series of experiments *On Magnetization by Rapid Oscillations, and on the Operation of the Rutherford-Marconi Magnetic Detector* has been made by E. Madelung, and described in his Göttingen Dissertation.[1]

By means of a very ingeniously devised application of Braun's cathode tube, Madelung was able to obtain on a fluorescent screen the hysteresis cycle produced by a slowly varying magnetic force, and to obtain also the effect produced on this hysteresis cycle by superposing the rapidly oscillating magnetic force produced by sending a condenser discharge through the magnetizing coils.

Reference is made to Fig. 104. I. With a slowly varying magnetizing force the hysteresis cycle $EAKFGE$ was described. II. Upon slowly applying and withdrawing a magnetizing force

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[1] E. Madelung: Drude's Annalen, 1905, Vol. 17, p. 861.

OM the curve *AKC* was obtained. III. On applying in the coil surrounding the specimen a rapidly oscillating electric current, giving a magnetizing force of initially the same amplitude *OM* and falling off in amplitude by damping, the spiral curve *AD* was described. IV. Applying a second oscillation gave a similar spiral starting with the arc *DJ*. The complete spiral for this case is not drawn; it is like that of *AD*, but is somewhat lower down. V. Applying more of these oscillations brought the spiral down into the position *L*, after which further oscillations simply caused the magnetization to describe over and over the closed spiral path *L*. The path *L* is thus the limit of the condition attained by the specimen when several oscillations are applied.

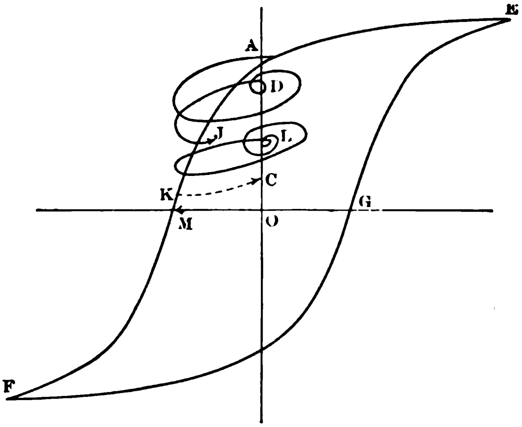

Fig. 104. Dr. Madelung's curve showing effect of rapid oscillations on magnetic hysteresis.

Thus a series of oscillations applied to the specimen originally in the state *A* reduced its magnetization to the state *L*.

The jump from *A* to *L* is the demagnetization effect of the oscillation, which was first utilized in the construction of a detector for electric waves by Rutherford.

Suppose now that these oscillations be applied to the specimen when it is in various different states of magnetization; Madelung found the effect shown in Fig. 105. Applied at *A*, the effect was a change from *A* to *B*; applied at *C*, the specimen, after the oscillation, was left almost in the state *C* unchanged; applied at *D*, the effect was a change from *D* to *E*. The effect of the oscillating field is thus a hastening of the progress of the cycle in the direction it was already going under the action of the slowly varying field.

A suppression of hysteresis would attain the same end results, but instead of being contented with calling the effect "suppression of hysteresis," which is a purely negative account of the phenomenon, Madelung, by his delineation of the spiral course taken by the magnetization during the application of the oscillating magnetic force, has given us a very distinct picture of the active processes occurring in the specimen. He has shown that the magnetic state of the iron has been violently agitated by the oscillating magnetic force, and in this way the sluggishness of the specimen in following the slowly changing magnetic force has been overcome.

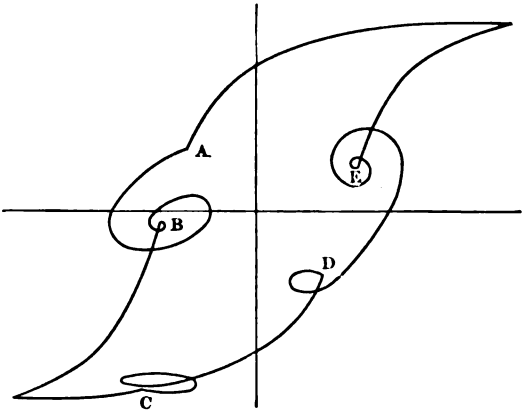

FIG. 105. High frequency oscillations superposed on different parts of cycle (Madelung).

Applying this process to our Fig. 103, we must think of the curve *B* as going through a set of vibratory tremors back and forth horizontally as it settles down toward the curve *H*. These tremors are of too high frequency to act on the telephone, which therefore responds only to the general displacement of the magnetization from the curve *B* toward the curve *H*.

Sensitiveness of the Magnetic Detectors. — The magnetic detectors are more sensitive than the coherer, but seem to be less sensitive than the electrolytic detector and some of the solid contact detectors (the crystal detectors).

THERMAL DETECTORS

There are two general classes of detectors in which the heat developed by the electric waves is made to manifest itself at the receiving station. In one of these classes, including the *bolometer* and the *barretter*, a change of electrical resistance under the heat developed is observed; and in the other class of thermal detectors, the *thermoelectric detectors*, it is the thermoelectromotive force called into play by heating the junction of two dissimilar metals that is observed.

Bolometer. — The Bolometer, which was applied by Paalzow and Rubens to measurements with electric waves, has been described in Chapter X (see Fig. 47). Briefly, the bolometer consists of an accurately balanced Wheatstone's bridge of which one arm is composed of a very fine wire. When electric waves are passed through this fine wire, it is heated. The heat developed changes the resistance of the fine wire and throws the bridge out of balance, so that the galvanometer in circuit with the bridge gives a deflection. This apparatus has been applied by Tisot to measurements of the energy received in a wireless telegraphic receiving station. The action of the bolometer is not sufficiently rapid for use in practical wireless telegraphy, unless one should use with it the newly developed Einthoven galvanometer, which has a very small period.

Barretter. — In a United States patent, for which application was filed June 6, 1902, Professor R. A. Fessenden has described a detector operating on the same principle of change of resistance with heat, but capable of being used with a telephone receiver. He calls the apparatus a *barretter*. In the construction of the barretter Professor Fessenden made use of a Wollaston wire, which is obtained by casting an ingot of silver with a platinum core and drawing down the ingot. This produces a wire with a silver exterior and a fine platinum thread running through the center. Then by etching off the silver with nitric acid from a short length of this wire the very fine platinum core is left. Fessenden's barretter consists of a small loop of

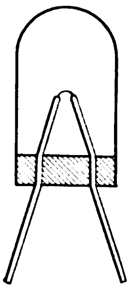

FIG. 106. Professor Fessenden's barretter.

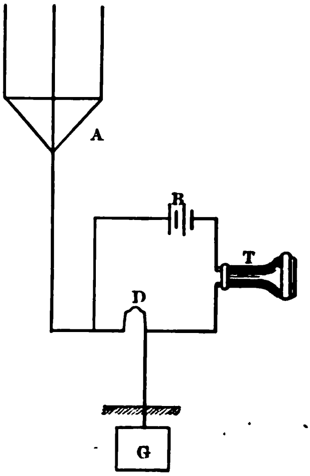

FIG. 107. Diagram of circuit with barretter as detector.

this fine platinum wire, which may be as small as one or two ten-thousandths of an inch in diameter. In the finished instrument this fine loop of wire is inclosed in a glass or metal bulb, as shown in Fig. 106. The method of using the detector is shown in Fig. 107, which contains the detector *D* in series with the antenna *A* and ground *G* of a receiving station. In the local circuit about the detector is a battery *B* and a telephone receiver *T*. Oscillations in the antenna circuit passing through the detector heat the fine loop of wire. This changes the resistance of the little loop, and consequently modifies the current in the local circuit, and produces a sound in the telephone receiver. When the waves cease the little loop rapidly cools, restoring the current to its original value. The adaptability of the instrument to the receipt of signals is due to the very small heat capacity of the fine wire, by reason of which it heats and cools with sufficient rapidity to respond with the train-frequency of waves. The difficulty with the use of this instrument arises in its liability to be burned out when the signals become too strong.

In sensitiveness the barretter falls far below the sensitiveness of the electrolytic and crystal detectors to be described later, and its use, except for the purposes of laboratory measurements, has been practically discontinued.

Thermoelectric Detectors. — We have already described two thermoelectric detectors: Klemenčič's thermal junction (Chapter IX) and Duddell's thermogalvanometer (Chapter XV). These instruments change the energy of the electric waves into heat localized in a small amount of metal. The heat developed, in the case of Klemenčič's thermal junction, is developed at the thermal junction itself; while in Duddell's instrument the heat developed in the " heater " is conveyed by radiation and convection to the thermal junction. The heating of the thermal junction produces an electromotive force, which gives rise to a unidirectional electric current in the local circuit and produces a galvanometer deflection. We have in these instruments, first, a change of the energy of the electric oscillation into heat, and then a change of this heat energy again into electric energy. The instruments of Klemenčič and Duddell, though very useful for the purposes of measurements, are not sufficiently rapid or sufficiently sensitive for use in the reception of actual messages.

It has been found, however, that a high resistance contact between a common metal and certain crystalline substances, or between two crystal substances, when connected with a telephone receiver, are highly sensitive to electric waves, and are among the most sensitive detectors known. These have been described in many cases by the patentees or by writers on the subject as *thermoelectric detectors.* It has been found, however, that in a great many cases, at least, the thermoelectric explanation of the phenomenon is not the correct explanation; and these detectors are described and discussed in the next chapter, under the head of *Crystal Rectifiers.*

CHAPTER XVII

ON DETECTORS (*Continued*).—CRYSTAL RECTIFIERS

We come now to a very sensitive and interesting class of detectors for receiving the signals of wireless telegraphy and wireless telephony. These are the detectors consisting of a self-restoring high-resistance contact between solid bodies, and since one of the bodies is usually crystalline in character, I have given to this class of detectors the name *Crystal Rectifiers.*

The crystal rectifiers are self-restoring, and are usually employed with a telephone receiver; but a capillary electrometer or galvanometer can be used in the place of the telephone receiver. Many of the detectors of this type will give a very strong response *without a battery in the local circuit,* but most of them require the battery of small e.m.f. for the best sensitiveness.

Fig. 108 shows the connections for use of a self-restoring detector with a battery *B* in the local circuit. Fig. 109 shows the detector without a battery. The detector *D* is shown attached to the antenna and ground in a very simple form of receiving circuit.

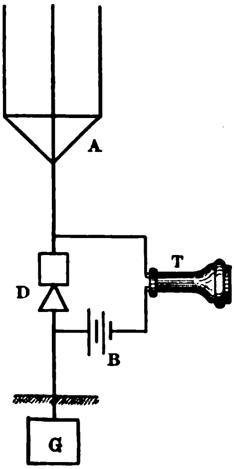

Fig. 108. Crystal contact detector with battery in local circuit.

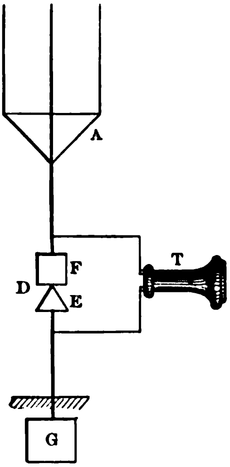

Fig. 109. Contact detector without battery.

Electric oscillations in the antenna pass through the detector, and a response is obtained in the telephone.

In the case of the use of the battery in the local circuit, we might explain the action by supposing that the resistance of the detector is changed by the electric oscillations through it (perhaps by the heat developed), and that in consequence of the change of resistance a larger or smaller amount of current is sent through the telephone receiver *T*.

In the case where no battery is employed (Fig. 109), we might explain the response in the telephone by supposing that the oscillations heat the contact *D*, and that the heat developed at the contact (which consists of two dissimilar bodies *E* and *F*) gives rise to thermoelectric currents in the circuit containing the telephone.

These are explanations that are apparently simple, and that apparently accord with many of the known facts about thermoelectricity. We shall see, however, in what follows, that a careful experimental study of the subject has led to the rejection of the thermoelectric explanation, and has brought us to regard the action of these detectors, as a case of the easier passage of electricity in one direction than in the other through the contact; that is to say, *we are dealing with a newly discovered case of rectification of an alternating electric current at a contact between solid bodies, and in this process of rectification heat plays only a negligible rôle.*

Before entering into a discussion of this view, let us describe some of these detectors of the self-restoring contact type. We shall begin with a rather poor representative, the *carbon microphone.*

Microphonic Detector. — In 1879, Professor D. E. Hughes, the inventor of the microphone, accidentally found that the contact of a piece of *carbon* with *bright steel,* when used with a telephone receiver, was responsive to the inductive effect produced by the make and break of the primary current of an induction coil. Hughes did not publish his results until interviewed on the subject by Mr. Fahie in 1899. He then wrote Mr. Fahie a letter, which was published in the *London Electrician,* May 5, 1899. In looking over the description of Professor Hughes's experiments we now see that in 1879 he was producing and receiving electric waves, and had discovered in the microphone a self-restoring contact detector. A diagram of one form of Hughes's microphonic detector is shown in Fig. 110, which is redrawn from a sketch in

Mr. Fahie's History.[1] In this diagram, *C* is a carbon pencil touching a steel needle *N*; *S* is a brass spring by which the pressure of the contact can be regulated. The adjustment of the spring is regulated by means of the disc *D*.

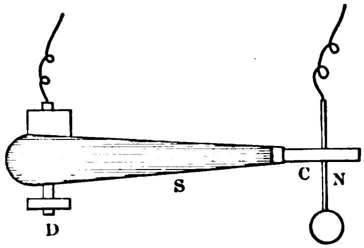

Fig. 110. Hughes's microphonic steel-carbon detector.

Professor Hughes used the microphone with or without a battery in the local circuit ; and when the battery was omitted, he attributed the sound in the telephone to the thermoelectromotive force developed at the carbon-steel junction. The detector was more sensitive with a battery in the local circuit than without it.

Various modifications of this microphonic detector of Hughes have been employed in practical wireless telegraphy. One modification, which had a considerable application a few years ago, is obtained by placing a steel needle across two blocks of carbon, as shown in Fig. 111. Another is made by placing a granule of carbon between metallic plugs in a tube, as shown in Fig. 112.

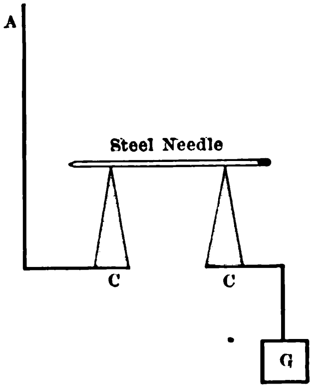

Fig. 111. Steel-carbon detector.

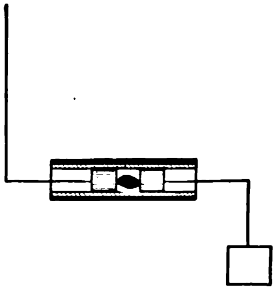

Fig. 112. Detector of carbon granule between metallic plugs.

The microphone is more sensitive than the filings coherers. It is, however, somewhat troublesome on account of sensitiveness to mechanical vibrations and on account of liability to cohere under strong signals, and it is surpassed in sensitiveness to electric

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[1] Fahie, History of Wireless Telegraphy, 1902, Dodd, Mead & Co.

waves by the crystal detectors, in which the carbon of Hughes's microphone is replaced by certain crystalline mineral substances.

Dunwoody's Carborundum Detector. — In 1906 General H. H. C. Dunwoody[1] of the United States Army (retired) discovered that a fragment of carborundum, when provided with suitable electrodes for connecting it into the circuit, will act as a receiver for electric waves. Carborundum is a carbide of silicon, manufactured in the electric furnaces at Niagara; it is a comparatively poor conductor of electricity, is crystalline in character, and is next to the diamond in hardness. In Dunwoody's description of the detector the connection of the carborundum into the circuit was made by twisting wires around the carborundum or by holding it in a clamp between metallic jaws supported on an insulating base. General Dunwoody found that when the carborundum detector was placed in a wireless telegraph receiving circuit, and a telephone was connected about the detector, responses were obtained in the telephone *with or without a battery on the local circuit.* The detector was, however, more sensitive with the battery than without it. A number of experiments on this form of detector have been described by the author in publications in the *Physical Review,* and are abstracted later in the present chapter.

The carborundum detector is not highly sensitive.

Austin's Tellurium-Aluminium and Tellurium-Silicon Detectors. — In 1906 Dr. L. W. Austin found that tellurium in contact with aluminium or in contact with silicon is a sensitive detector for electric waves with or without a battery in the local circuit. He attributed the action to thermoelectricity in his patent applications and early writings[2] on the subject, but afterwards found that this was not the true explanation of the phenomenon.[3]

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[1] Dunwoody: U. S. Patent, No. 837,616, filed March 23, 1906, issued Dec. 4, 1906.

[2] L. W. Austin: Letter to the Electrical World, 1906, Vol. 48, p. 924; U. S. Patent, No. 846,081, filed Oct. 27, 1906, issued March 5, 1907; "The High Resistance Contact Thermo-Electric Detector for Electrical Waves." Physical Review, 1907, Vol. 24, p. 508.

[3] After the publication of the author's research on the Carborundum Detector (See Pierce: "Crystal Rectifiers for Electric Currents and Electric Oscillations, Part I, Carborundum." Physical Review, 1907, Vol. 25, p. 31), in which it was pointed out that thermo-electricity could not explain the phenomenon, Austin came to the opinion that the action in the case of his tellurium detector and other detectors of a similar type was also not thermoelectric.

Pickard's Crystal Detectors. — Mr. Greenleaf W. Pickard has been very prolific in the discovery of materials of a crystalline character that can be used as a member of contact detectors. Among the substances used and patented by him in this connection are silicon,[1] zincite,[2] chalcopyrite,[3] bornite and molybdenite.[4]

The mounting of Mr. Pickard's silicon detector, which is representative of a favorable method of constructing the detectors of this class, is shown in Fig. 113. A rod of brass *A* is pressed down by a spring *S* into contact with a mass of polished silicon *B*, embedded in an easily fusible solder of Wood's metal, *M*. The solder in which the silicon is embedded is contained in a metallic cup *P*, which rests upon a metallic plate *K*. Connection to the rod *A* is made by means of the binding post *E*. Connection to

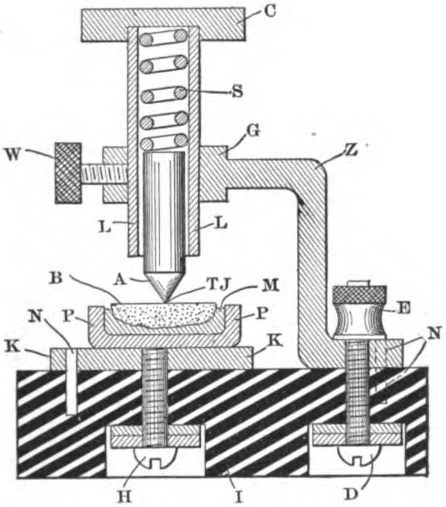

Fig. 113. Pickard's silicon detector.

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[1] G. W. Pickard: Electrical World, Vol. 48, p. 1003, 1906; U. S. Patent, No. 836,531, filed Aug. 30, 1906, issued Nov. 20, 1906; U. S. Patent, No. 888,191, filed Nov. 9, 1907, issued May 19, 1908.

[2] G. W. Pickard: U. S. Patent, No. 886,154, filed Sept. 30, 1907, issued April 28, 1908.

[3] G. W. Pickard: U. S. Patent, No. 912,726, filed Oct. 15, 1908, issued Feb. 16, 1909.

[4] G. W. Pickard: U. S. Patent, No. 904,222, filed Mch. 11, 1907, issued Nov. 17, 1908.

the silicon is made by means of a binding post not shown, which connects with the plate *K*. The ability to move the cup containing the embedded silicon is an advantage, because not all parts of the silicon surface are equally sensitive, and this motion permits the selection of a sensitive place on the silicon as the point of contact. Mr. Pickard sometimes uses two of these active materials in the same detector. For example, a contact of zincite with bornite is one of the most sensitive electric wave detectors known.

The action of these detectors was at first attributed by Mr. Pickard to thermoelectric effects, but after I had published the opinion that the action was not thermoelectric, Mr. Pickard amended many of his patents to comply with this latter view.[1]

EXPERIMENTS CONCERNING THE ACTION OF THE CARBORUNDUM DETECTOR AND THE OTHER CRYSTAL-CONTACT DETECTORS

Soon after the discovery by General Dunwoody that a crystalline mass of carborundum when supplied with a contact electrode acts as a detector for electric waves, I began a series of experiments to determine, if possible, the nature of the phenomenon. The experiments were extended to other crystal detectors. The results of these experiments have been published in the *Physical Review* in a series of papers entitled " Crystal Rectifiers for Electric Currents and Electric Oscillations." [2] The method of experimenting consisted —

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[1] It is not safe to take the date of application for a patent as the date of the discovery of all the facts contained in the patent, because there is nothing in the published patent to show whether the matter of the specifications and claims was introduced at the date of the application or much later, *as amendments*. The actual date of the amendments can be obtained from the file records in the patent office.

Sometimes a patentee, without any intention of obtaining undue credit for priority, but in accordance with ordinary United States Patent Office practice, and by reason of interference with another inventor, has had discoveries put into his patent application that were not there when the application was made.

[2] G. W. Pierce: Crystal Rectifiers, etc. Part I. Carborundum, Physical Review, Vol. 25, p. 31, 1907. Part II. Carborundum, Molybdenite, Anatase, Brookite, Physical Review, Vol. 28, p. 153, 1909; and Proc. Am. Acad. of Arts and Sciences, Vol. 45, p. 317, 1909. Part III. Iron Pyrites, Physical Review, Vol. 29, 1909. See also G. W. Pierce: A Simple Method of Measuring the Intensity of Sound, Proc. Am. Acad. of Arts and Sciences, Vol. 43, p. 377, February, 1908.

(1) In determining what currents would flow through the detector under a given steady electromotive force;

(2) In an oscillographic study of the instantaneous values of the current through the detector under the action of .an alternating e.m.f.;

(3) In measuring the thermoelectric properties of some of the specimens and comparing the thermoelectromotive force with the rectified current.

Some of the facts obtained in these experiments are presented in this and the next chapter.

Apparatus for Current-voltage Measurements. — Figure 114 shows a sketch of a form of circuit employed in studying the conductivity of crystal contact under various conditions, by means of current and voltage measurements. The crystal, held in a clamp, is shown at *Cr*; *B* is a storage battery; *XYZ* is a potentiometer consisting of two fixed plates of zinc *X* and *Z*, and one movable plate *Y*, immersed in a zinc sulphate solution. By means of the voltmeter *V* the difference of potential between the plates *Y* and *Z* could be read, and the resulting current through the crystal was given by a galvanometer or milliammeter at *A*. The resistance of the galvanometer was so small in comparison with the resistance of the crystal that the reading of the voltmeter was practically the drop of voltage in the crystal.

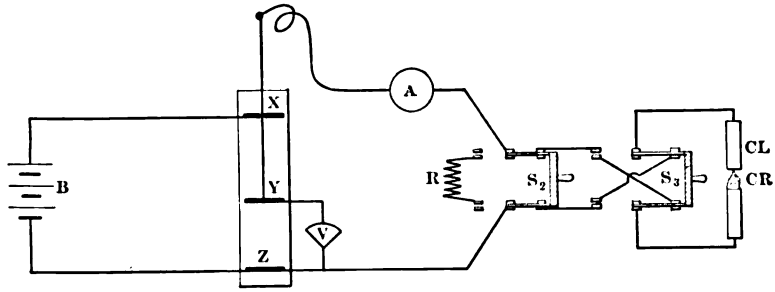

FIG. 114. Circuit for studying current-voltage characteristic of crystal rectifiers.

The switch S_3 enables the observer to reverse the current in the crystal under examination without reversing the galvanometer. A known resistance at *R* could be thrown into circuit with the galvanometer for the purpose of calibrating it.

Current-voltage Curve for the Carborundum Contact. — A curve obtained by plotting the current against voltage in an experiment with carborundum is shown in Fig. 115. It is seen that the current through the carborundum is not proportional to the voltage impressed upon it; the apparent resistance of the carborundum or its contact diminishes with increasing current.

Experiments were made by the writer on a great many specimens of carborundum and other crystal detectors, and curves of approximately the shape shown in Fig. 115 were obtained in all the cases.

On reversing the electromotive force so as to send the current in the opposite direction through the contacts a most interesting property was discovered; namely, the property of unilateral conductivity.

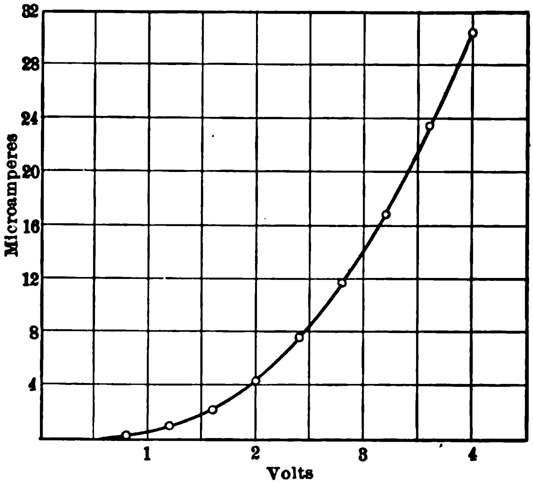

Fig. 115. Current-voltage curve of a carborundum contact.

Unilateral Conductivity of the Carborundum Contact. — The current through the crystal in one direction under a given electromotive force was found to be different from the current in the opposite direction under the same electromotive force; that is to say, the heterogeneous conductor formed of the crystal and its contacts is unilaterally conductive. This effect may be seen by a reference to Fig. 116. The branch *I* of the curve shows the current, plotted against voltage, when the current is in one direction;

branch *II* the corresponding values of the current obtained when the voltage is reversed. The accompanying table, Table III, contains the numerical values from which these curves were plotted.

In the experiment whose result is shown in Fig. 116 and Table III, the specimen of carborundum was held in a clamp under a pressure of about 500 grams, and it is seen from the table that the current in one direction is 100 times as great as the current in the opposite direction when an electromotive force of 10 volts is applied in the two cases. With increase of current through the specimen, the ratio of the current in the two opposite directions diminishes. At 27.5 volts C_1 is only 17 times C_2.

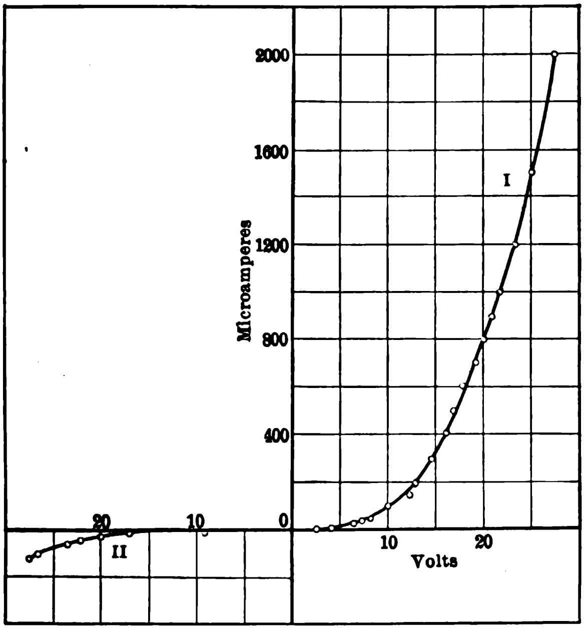

Fig. 116. Curve showing the carborundum contact to be unilaterally conductive.

In this particular experiment the piece of carborundum was submerged in an oil bath designed to keep the temperature of the specimen constant. The piece of carborundum was held in a clamp, the jaws of which served to lead the current to the specimen. The oil, of which the temperature was 64° C., came freely into contact with the crystal.

TABLE III

RELATION OF CURRENT TO VOLTAGE, SHOWING UNILATERAL CONDUCTIVITY OF A CARBORUNDUM CONTACT

Volts.	Current in Microamperes.		C_1/C.
	C_1 Commutator, Left.	C_2 Commutator, Right.	
2.2	1		
2.8	2		
4.0	5		
4.7	10		
5.9	20		
6.5	30		
7.3	40		
8.0	50		
10.0	100	1	100
12.1	150		
12.8	200		
14.5	300	5	60
16.0	400		
16.8	500	10	50
17.7	600		
19.4	700		
20.0	800	20	40
21.0	900		
21.9	1,000	30	33
23.2	1,200	50	24
25.0	1,500		
27.5	2,000	120	17

Similar effects were obtained at various temperatures between −10° C. and 100° C., both with and without the use of oil as a bath. A like result was had with different specimens and under different pressures. The relative values of the positive and negative currents, however, varied from piece to piece, and also was different under different conditions of temperature and pressure.

Effects of Pressure. — Figure 117 shows a series of current-voltage measurements with a specimen of carborundum held in a clamp under various pressures.

Several experiments were made with other specimens of carborundum with considerable disparity in the results, and the curves of Fig. 117 cannot be taken to represent a general occurrence.

For more details on the effect of pressure reference is made to the original publications in the *Physical Review.*

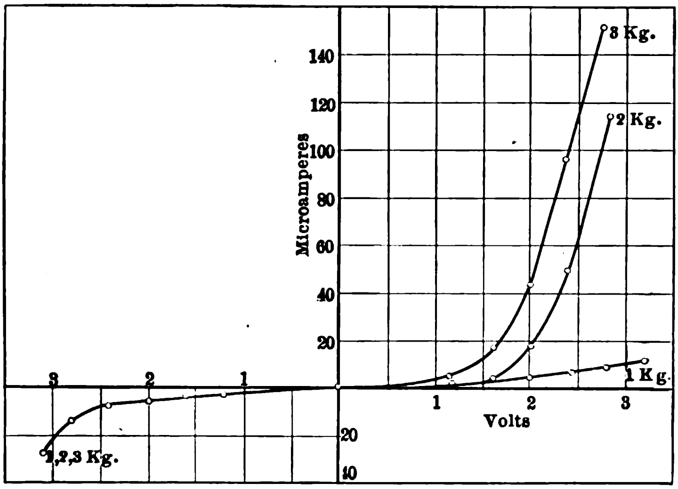

FIG. 117. Current-voltage curves of carborundum under different pressures.

Experiments with Platinized Specimens of Carborundum. — In the effort to ascertain what part the form of contact plays in the phenomenon of unilateral conductivity in crystals, a number of specimens of carborundum were selected with opposite faces plane and very approximately parallel, and some of the parallel-faced crystals were platinized on one or both of their smooth surfaces by the cathode discharge so that they could be put into good conducting contact with the electrodes. The metallic surfaces thus obtained were in many cases optically plane.

Platinized on One Face only. — Some of the specimens, platinized on one face only, gave very remarkable unilateral conductivity. Table IV shows results obtained with one of these specimens, designated 11_b, when submitted to a pressure of 1 kilogram. This specimen was .6 mm. thick, with area of about 1 sq. mm. One of the faces, which was optically true, was heavily platinized. The other face was somewhat rough and was without platinum. The specimen was held in a clamp with silver jaws.

TABLE IV

CRYSTAL, 11b. THICKNESS, .6 MM: AREA, 1 SQ. MM. PLATINIZED ON ONE SIDE. PRESSURE, 1 KG.

Volts.	C_1, Current toward Platinum in Microamperes.	C_2, Current from Platinum in Microamperes.	C_1/C_2.
4.5	3.92	Too small to measure with the instrument used.	
6	7.84		
7	19.6		
9	39.2		
10	64.0		
11	98.0		
13	168		
15	282		
16	350		
18	600		
21	1000		
26	2000		
30	3000	.75	4,000
34.5	4200	3.92	1,070

Careful examination showed that the rough, unplatinized face of the crystal made contact at only a few points with the electrode on that side. With a given voltage, the current *toward* the platinized face was *greater* than the current in the opposite direction, and the conductive asymmetry of the crystal, having, as it did, one good conducting and one high-resistance contact, was very great. At 30 *volts the current toward the platinized face was* 4000 *times the current in the opposite direction.* The results for this specimen under a pressure of 1 kg., and also under a pressure of .35 kg., are plotted in the curves of Fig. 118. The current toward the platinized face is given in the right-hand quadrant. The current in the opposite direction does not appreciably depart from the axis.

When the pressure was increased to 2 kg., and then to 3 kg., the currents in both directions were increased and the ratio of C_1/C_2 was reduced, so that the current toward the platinum was only two or three times as great as the current in the opposite direction for a given voltage.

Carborundum Platinized on Both Sides. — When a specimen of carborundum was platinized on two sides so as to make relatively good conducting contact with both electrodes of the clamp, the

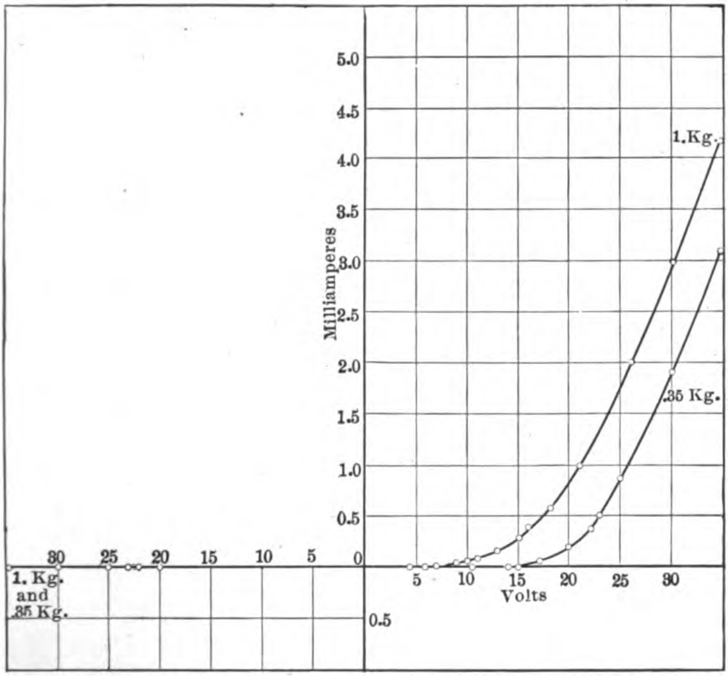

FIG. 118. Curve of a carborundum contact showing remarkable unilateral conductivity.

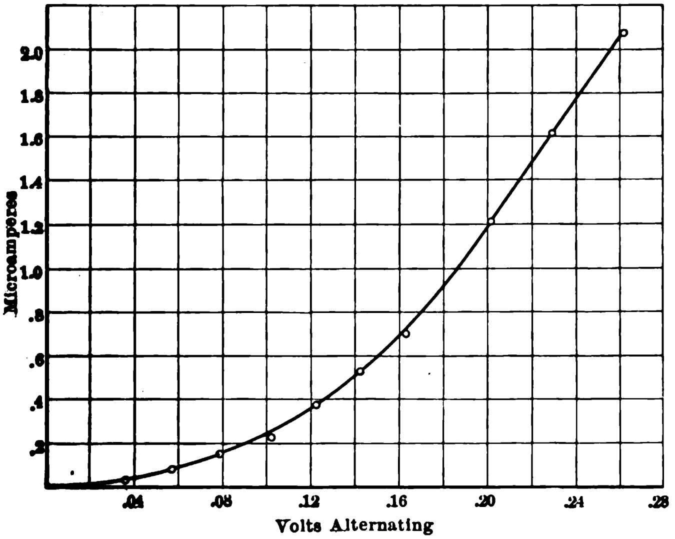

FIG. 119. Rectification of alternating current by a crystal-contact detector.

ratio C_1/C_2 of the current in the two opposite directions was only 1.1–1.6 instead of 4000, as it had been in the previous experiment. A set of the observations with the specimen platinized on both faces is given in Table V.

TABLE V

SPECIMEN NO. 19, PLATINIZED ON BOTH SIDES. THICKNESS .82 MM. AREA 5 SQ. MM.

Volts.	Current in 10^{-4} Amperes.		C_1/C_2.	Apparent Resistance in Ohms.	
	C_2.	C_1.		R_1.	R_2.
1	1.5	2.0	1.36	6660	5000
1.5	6.0	10.0	1.66	2500	1500
2	9.5	15	1.59	2100	1330
3	20	30	1.50	1500	1000
4	37.9	54.2	1.42	1060	740
5	68	95	1.40	735	530
6	109	150	1.37	550	400
7	152	210	1.38	455	332
8	217	288	1.33	370	280
9	278	370	1.33	323	243
10	380	485	1.28	263	207
11	460	620	1.35	240	178
12	580	780	1.35	207	154
13	760	970	1.28	171	134
14	920	1110	1.22	152	125
15	1100	1450	1.32	136	103
16	1350	1700	1.26	119	94
17	1650	2000	1.21	102	85
18	2000	2450	1.23	90	73
19	2500	2830	1.13	76	67
20	2940	3600	1.23	68	55
21	4200	4820	1.13	50	43

Rectification of Alternating Currents by the Crystal Contact. — In the previous experiments it has been shown that the carborundum contact is unilaterally conductive; that is, it gives a greater current in one direction than in the opposite direction when the same electromotive force is applied in the two cases. If this property is manifested for rapid reversals of voltage, an alternating voltage ought to give more current in one direction than in the other. The contact ought, therefore, to serve as a rectifier for alternating currents. Experiment shows this to be true not only for the carborundum detector but for all the crystal contact detectors. For example, the curve of Fig. 119 was obtained with the molybdenite detector, by measuring with a galvanometer the direct current through the detector when various values of 60-cycle alternating voltage were applied to the circuit containing the detector and galvanometer in series. We shall present in a subsequent chapter some oscillograms obtained with the crystal rectifiers. Let us, however, first see how a rectifier for small alternating currents may be a detector for electric waves.

RECTIFIERS AS DETECTORS

Having seen in the preceding paragraphs that certain crystal contacts are rectifiers of alternating current, let us now reconcile this characteristic of the sensitive contacts with their action as a detector for electric waves.

Two Characteristics. — For the purposes of this discussion [1] we need to fix our attention upon two important characteristics of the sensitive contacts above investigated.

First, the current is not proportional to the voltage; and second, the current in the two opposite directions is not the same under the same applied voltage.

A detector may possess one of these characteristics without the other, or may possess both together. A conductor or a combination of conductors possessing the first of these characteristics has,

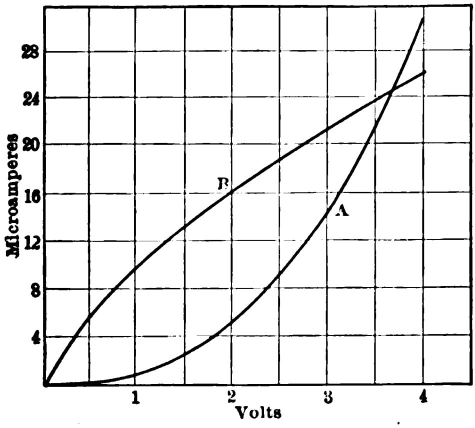

FIG. 120. Rising current-voltage characteristic (curve *A*) and falling current-voltage characteristic (curve *B*).

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[1] In this we are following very closely the arguments laid down by H. Brandes, Elektrotechnische Zeitschrift, Vol. 27, pp. 1015–1017, 1906, and Science Abstracts, No. 2078, Vol. 9, 1906.

we shall say, a " rising " or " falling " characteristic. (Compare respectively curves *A* and *B*, Fig. 120.) A conductor or combination of conductors showing unequal currents in opposite directions under the same applied voltage we have called "unilaterally conductive."

Now a unilaterally conductive system is seen at once to be a *rectifier* for alternating currents, without any battery in the circuit, because when an alternating voltage is applied, more current flows in one direction than in the other.

A conductor or system of conductors having a rising or falling current-voltage characteristic, is a *rectifier* also, if used with an auxiliary direct current upon which the alternating current is superposed. In explanation of this statement, let us suppose such a detector *D*, Fig. 121, to be inserted in series with a galvanometer *G*, a battery *B*, and a source of alternating voltage *AC*. Let us suppose that the conductor *D* has a current-voltage characteristic of the form shown by curve *A*, Fig. 120. Let the e.m.f. of the battery be 2 volts. By a reference to the current-voltage curve it will be seen that this will send a direct current of 5.3 microamperes through the circuit. Now let the impressed alternating voltage have a maximum e.m.f. of ½ volt. When this is in one direction it will add to the 2 volts direct, giving 2.5 volts. The corresponding current, from the curve, is 9.2 microamperes. When the alternating e.m.f. is in the opposite direction, it will subtract from the local voltage, giving a total voltage of 1.5 volts. The corresponding current, from the curve, is 2.7 microamperes. Thus, under the action of the impressed e.m.f. of ½ volt (maximum) the current fluctuates between 9.2 and 2.7 microamperes. All of the intermediate values can also be obtained from our knowledge of the impressed voltage and the current-voltage curve *A*. However, without such a general investigation it is seen that the added voltage from the alternating source increases the current in one direction more than the corresponding subtracted voltage decreases it; and that consequently the total effect of the superposed alternating voltage is an increase of current. In this way

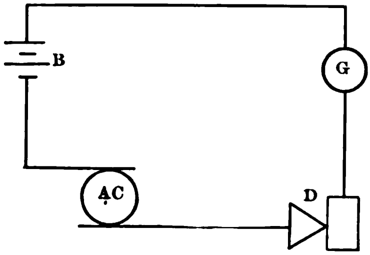

FIG. 121. Detector in circuit with alternating e.m.f.

an increment of direct current is obtained by the superposition of an alternating voltage upon the local direct voltage; that is to say, the apparatus is a *rectifier*.

In a similar way, it may be shown that if the conductor D has a *falling* characteristic, it also has a rectifying effect, if used with a local battery; but in this case the effect of the impressed alternating e.m.f is to produce a decrease in the local current.

Now a crystal contact which is *asymmetrically conductive* and has also a *rising* characteristic will be a rectifier without a battery and also with a suitable battery in the local circuit. Whether it will be a better rectifier with or without the battery depends on the form of the current-voltage characteristic.

WHY A RECTIFIER FOR SMALL ALTERNATING CURRENTS ACTS AS A DETECTOR FOR ELECTRIC WAVES

In the preceding sections we have seen that the detectors that have certain characteristics are rectifiers for alternating currents. In our illustration we applied our alternating e.m.f. directly to the circuit containing the detector and the galvanometer, or telephone, in series. But when the detector is used in a wireless telegraph receiving circuit, the alternating e.m.f. is not so applied, and furthermore has a very high frequency. How is the action of the detector to be explained in that case?

Let us take the case of the simple form of receiving circuit shown in Fig. 122, with or without a battery in the telephone circuit.

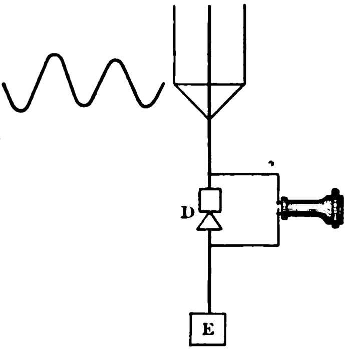

Fig. 122. Detector in antenna circuit.

A train of incoming waves produces an alternating e.m.f. in the antenna circuit. This e.m.f., when in one direction, produces a large current through the detector, D, charging the antenna. When the e.m.f. reverses, the current from the antenna to the ground through the carborundum is smaller, thus leaving the antenna charged with a small quantity of electricity. The effect of the whole train of waves is additive, so that this charge on the antenna is cumulative. The accumulated charge on the antenna escapes through the telephone shunted about the carborundum, causing the diaphragm to move. Each subsequent train of waves causes a similar motion of the diaphragm, which is evidenced as a note in the telephone with the train frequency of the waves.

It is immaterial whether the detector permits the larger current to flow upward, charging the antenna positive, or permits the larger current in the downward direction, charging the antenna negative. The explanation is the same in both cases.

With very slight change this explanation can be made to apply also to those cases in which the detector is in a condenser circuit coupled inductively or directly with the antenna circuit.

CHAPTER XVIII

ON DETECTORS (*Continued*)

FURTHER EXPERIMENTS ON THE CRYSTAL RECTIFIERS

HAVING seen in the preceding chapter that the crystal contacts, when suitable crystals are employed are *detectors* for electric waves because they are *rectifiers* for rapid alternating currents, let us experimentally investigate the subject a little further.

Questions Arising in Connection with the Phenomenon. — Many interesting questions arise in connection with the phenomenon. Is the action localized at the surface of contact between the crystal and the metallic electrode ? Is the action due to electrolytic polarization? Is the action thermoelectric, conditioned on unequal heating of the two electrode contacts ? If the phenomenon is novel, how is it related to the hitherto studied properties of conductors?

In the experiments on carborundum, performed by the writer and partially presented in the preceding chapter, the investigation of these questions met with limitations on account of the form of occurrence of the carborundum in discrete masses to which electrodes could not be rigidly attached, so that the conditions at the electrodes could not be widely varied. However, by increasing the pressure of the electrodes against the carborundum beyond a certain limit, and by cathodically platinizing the surfaces of the carborundum at both the contact areas, we have seen that the rectification, though not entirely eliminated, was rendered very imperfect; that is to say, the ratio of the strength of the current in one direction to that in the reverse direction approached unity. On the other hand, platinizing one only of the surfaces of contact, while the other surface was left unplatinized, generally rendered the rectification more nearly perfect. This fact indicated that the seat of the action was the area of contact with the electrodes, and that the action at the two contacts were usually in opposition to each other, so that when the action at one of the contacts was reduced by platinizing, the rectification at the other contact appeared more pronounced.

These characteristics of the phenomenon are consistent with the view that *the rectification is conditioned on the localization of the energy of the circuit at the high resistance boundary between the two different conductors*, the crystal and the electrode.

Now such a localization of energy at the boundary of the two conductors is favorable to the production of electrolytic polarization, if we may have electrolytic polarization in solids, and is also favorable to the production of a thermoelectromotive force, either of which might result in rectification.

Nevertheless, a number of experiments have been made which indicate that neither electrolysis nor thermoelectricity plays an important part in the phenomenon.

On the question of electrolysis, the following experiment has a bearing.

Experiment Showing Permanence of the Carborundum Rectifier. — In confirmation of the absence of electrolytic polarization, a durability test of the carborundum rectifier has been made as follows: A crystal of carborundum inclosed in a glass tube with a few drops of oil and held between brass electrodes, one of which was pressed forward by a spiral spring, was kept under almost daily observation[1] from October 23, 1907, until March 18, 1908. During these five months more than 1200 measurements were made of the direct current obtained through the crystal under different direct and alternating voltages. The rectifier was kept in a temperature bath and was subjected to various long periods of heating and cooling ranging from 0° to 80° C. Notwithstanding the long continued exposure of the crystal to large changes of temperature, and notwithstanding the frequent loading of the rectifier with current, it was found at the end of the series that the values of the direct current obtained from the crystal under a given applied alternating voltage over a range of current from 4 to 400 microamperes (direct) and a range of voltage between 1.5 and 6 volts (alternating) did not differ from the corresponding values at the beginning of the series by an amount exceeding the limit of accuracy of the experiment, which was about $\frac{1}{3}$ of 1 per cent.

This experiment shows that if there is any kind of electrolytic

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[1] This series of measurements was carried out by Mr. K. S. Johnson, to whom the writer wishes to express his sincere thanks. The experiment was finally discontinued on account of the accidental melting of the cement holding in the ends of the tube.

action, it must be of such a character as to change the nature of the electrodes or of the crystal only very slowly, if at all.

On the Question of a Possible Thermoelectric Origin of the Phenomenon. — It is apparent that the disposition of the crystal, with a high-resistance contact of a metal against it at one side and usually a comparatively low-resistance contact at the other side, is exactly the most favorable for the development of heat at the high resistance junction. This heat being localized at a very small area, would raise the temperature of that area considerably. Now when the junction of two dissimilar conductors (e.g., bismuth and antimony) is heated, an electromotive force is developed at the junction. And for all we know, unless we try it, the contact of the crystal with the metal may have an enormously higher thermoelectromotive force developed than that developed at previously known thermal junctions.

If this is true, then when the current is in one direction the thermoelectromotive force would add to the applied voltage and produce an excessive current, while with the current in the opposite direction the thermoelectromotive force would subtract from the applied voltage and produce only a small current. This explanation of the phenomenon seems at first alluringly simple, and has been adopted by a number of writers and inventors, some of whom have, however, afterwards changed their views. But many persons still hold to the idea that these crystal-contact detectors are thermoelectric detectors, and they are so described in many trade catalogues, especially in Europe.

In fact, there is so much genuine circumstantial evidence in support of the thermoelectric hypothesis, that it seems very important to present with some thoroughness the experimental facts that exclude this hypothesis.

Extension of the Experiments to Other Crystals. — In order to carry out such an investigation a search was made for other crystals showing properties similar to carborundum but occurring in a form more suitable for study. After anatase and brookite and molybdenite had been discovered to be rectifiers and had been tested, it was found that the required conditions were best fullfilled by molybdenite.

I shall therefore describe the molybdenite detector. I shall then show and describe some oscillograms of alternating current through several crystal detectors, and shall afterwards return to some thermoelectric experiments.

MOLYBDENITE

One of the most sensitive of the rectifiers thus far investigated makes use of molybdenite as a member.[1] Molybdenite, with the chemical formula MoS_2, is a mineral occurring in nature in the form of tabular hexagonal prisms with eminent cleavage parallel to the base of the prism. The cleavage of the crystal resembles that of mica, and thin sheets of the mineral several square centimeters in area may be scaled off from a large crystal of molybdenite. These sheets have a metallic luster and look not unlike sheets of lead foil. *They can be readily electroplated with copper, so that connecting wires may be soldered to them.* This property, together with the thinness of the sheets and the ease with which the thermoelectric property of the substance may be studied, admirably adapts it to the present experiments.

The Molybdenite Rectifier. — The molybdenite rectifier also acts as a receiver for electric waves without a battery in the local circuit.

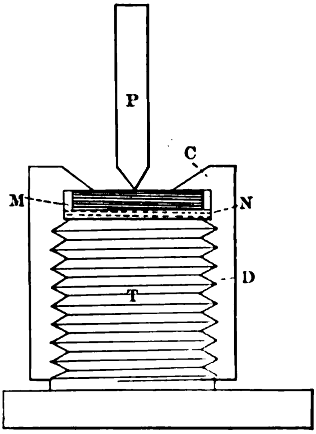

Fig. 123. Holder for molybdenite.

A form of mounting for the molybdenite is shown in section in Fig. 123. *T* is a threaded brass post on the top of which is placed a disc of mica, *N*. On top of the mica is a thin circular disc of the molybdenite *M*, with an area of about 1 square centimeter, leaving a projection of the mica beyond the periphery of the molybdenite. A hollow cap, *D*, threaded inside and having a conical hole at the top, is screwed down on the post *T* so as to clamp the molybdenite between the mica disc[2] and the annular

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[1] See also G. W. Pierce: " A Simple Method of Measuring the Intensity of Sound," Proc. Am. Acad. of Arts and Sciences, Vol. 43, p. 377 (Feb., 1908), in which the Molybdenite Rectifier was employed. This detector was also independently discovered by Mr. Greenleaf Whittier Pickard.

[2] The purpose of the mica disc under the molybdenite is to confine the current as much as possible to the upper layer of the molybdenite. This was done so as not to complicate the phenomenon by conduction across the laminæ of the substance, and also so that when the detector is immersed in oil in some of the later experiments, the oil shall have free play over the conducting surface and over the contacts, and serve the better to avoid possible changes of temperature of the essential parts of the apparatus.

shoulder of the cap, with the upper surface of the molybdenite exposed above. At the free surface of the molybdenite contact is made [1] with the metallic rod *P*.

The rod *P* was either supported unadjustably, as in the author's experiments on sound, or it was mounted in a manner to permit of ready adjustment, as is shown in Fig. 124. The clamp *K* containing the molybdenite is metallically connected with the binding post *H* (Fig. 124). Another binding post is attached to the metallic block *A*, on top of which is supported a stout spring *B*. Through a hole in *B* provided with a set-screw, the rod *P* is allowed to drop down into contact with the surface of the molybdenite at *K*. The set-screw is then tightened against *P*, and the final adjustment is made by the slow-motion screw *S*. The apparatus is connected in circuit by means of the binding posts, so that the current of the circuit is made to enter the molybdenite through the contact area between *P* and the molybdenite and leave by way of the contact between the molybdenite and the cap *C*, or the reverse. It is found that a much larger current flows in one direction than in the reverse direction for a given applied electromotive force.

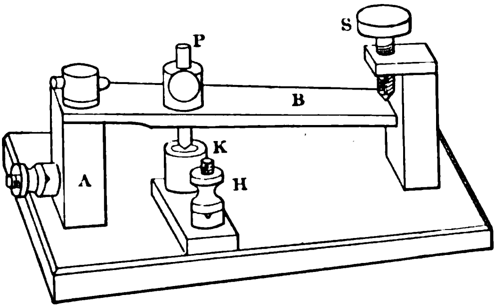

FIG. 124. Mounting for molybdenite.

The current-voltage curves (see Figs. 125, 126 and 127) resemble those of the carborundum detector, but large rectified currents

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[1] In the diagrams of Fig. 123 and Fig. 124 the lower end of the rod *P* is shown pointed. It is found, however, that the end of the rod *P* may be blunt or even flat with an area as great as 4 sq. mm. without much loss of sensitiveness of the instrument as a receiver for electric waves or as a rectifier.

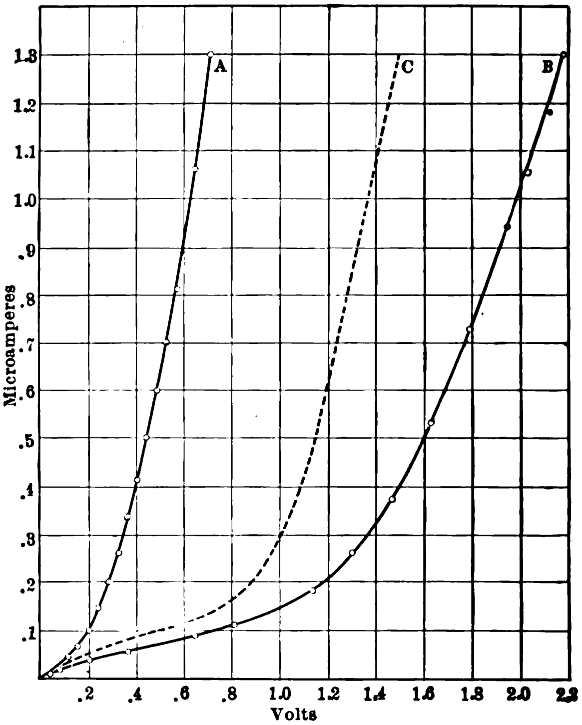

FIG. 125. Current-voltage curves of the molybdenite rectifier. *A*, current from copper to molybdenite; *B*, current in opposite direction; *C*, difference of voltage for a given current.

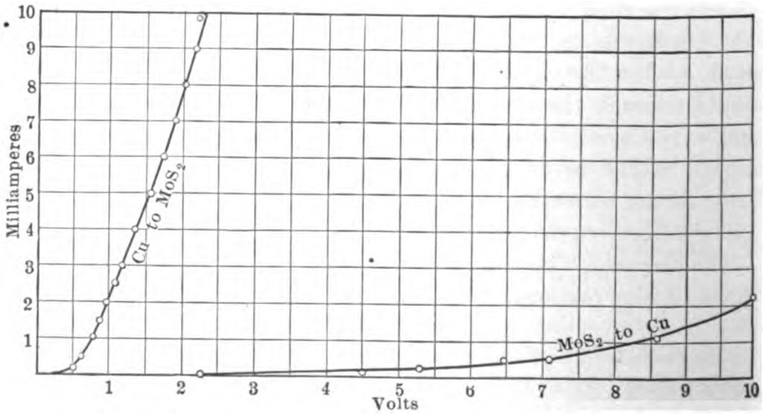

FIG. 126. Current-voltage curves with molybdenite rectifier.

are obtained with very small voltages in the case of the molybdenite, which characterized the molybdenite rectifier as much more sensitive than the carborundum as a detector for electric waves.

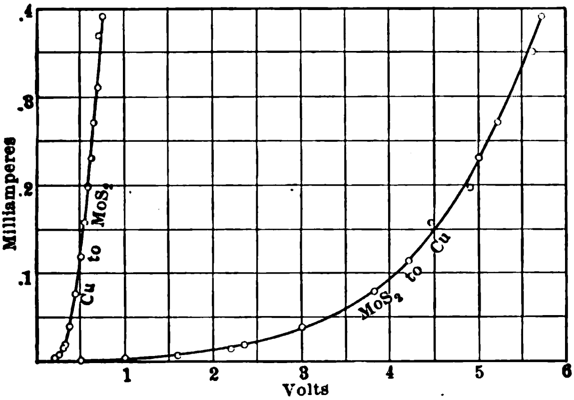

Fig. 127. Current-voltage curves with molybdenite rectifier.

OSCILLOGRAPHIC STUDY OF CRYSTAL RECTIFIERS

An oscillogram is a photograph showing the rapidly changing values of the current in a circuit when a rapidly changing voltage is applied to it. In the case of the crystal rectifiers a current of only a few thousandths of an ampere could be sent through the crystal contact without destroying its rectifying power. It was therefore necessary to employ a very sensitive apparatus, — one that would deflect with these small values of the current, and would reverse when the current reversed, and that at the same time would be so rapid in its action as not to show any appreciable lag when the current through it was rapidly changing. The purpose of the experiment was to see if the current changes in the detectors followed the voltage changes at once or if they lagged behind, as would be the case if the action of the detector depended on heating or cooling, because heating and cooling require time. Also, if electrolytic action entered into the phenomenon it ought to show in the oscillograms.

After much experimenting the necessary sensitiveness of apparatus was finally obtained with a Braun's cathode tube oscillograph. This apparatus makes use of the fact that when a high electromotive force, say 20,000 volts, is applied to two aluminum electrodes sealed into a glass tube, from which the air is pumped to a sufficiently high degree of exhaustion, a stream of negatively charged particles called the cathode stream is shot out from the negative electrode, and these particles of the cathode stream travel away in a straight line perpendicular to the negative electrode.

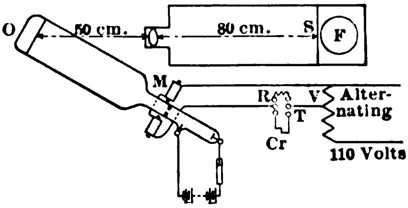

FIG. 128. Oscillographic apparatus.

Reference is made to Fig. 128. The small flat disc in the small end of the tube is the cathode The cathode particles are sent lengthwise the tube, and in Professor Braun's apparatus are made to pass through a small diaphragm so as to limit the beam to a small cross section. Beyond the diaphragm the beam passes through the center of the enlarged portion of the tube and makes a bright spot upon a fluorescent screen at *O*. Now when a magnet is brought up near the tube at *MM*, the cathode beam is deflected so that the bright spot at *O* moves perpendicular to the page. When the magnet is reversed, the deflection of the spot is reversed.

If instead of using a permanent magnet at *MM* we use electromagnets, as shown in the figure, and if we send an alternating current through the coils of the electromagnets, the deflection of the spot is first in one direction and then in the other, back and forth across the screen at *O*. A photographic camera, (Fig. 128) is placed above the cathode tube, and an image of the spot *O* is focused on the film carried by a drum *F*. The image plays back and forth across the film. If now the film is set in motion by a rotation of the drum, the to and fro moving spot traces a wavy line on the film. The drum is driven at a high speed, and in order that the wavy line on the film may come back on itself with each revolution, the drum must be driven synchronously with the alternating current which is being oscillographed. This was attained by driving the drum with a synchronous motor operating on the same alternating current source of 60 cycles. The synchronism of the drum with the deflections of the luminescent spot was so perfect in the present experiments that exposures of four minutes could be made, during which time the image of the spot moved over the sensitive film 4800 times, without any failure of perfect superposition, and without any appreciable fogging of the film.

The deflecting electromagnets *MM* had a combined resistance of 436 ohms, and were provided with soft iron cores about 6 millimeters in diameter. With these deflecting coils a direct current of 1.5 milliamperes gave a deflection of 1 cm. on a ground glass put in the place of the sensitive film at the back of the camera. A calibration for different values of direct current through the coils showed the deflections of the light spot to be proportional to the current, for the small values of the current employed, and showed no evidence of hysteresis in the iron.

The Oscillographic Photographs. — Reproductions (reduced to ⅓) of a characteristic set of the photographs obtained with a 60-cycle alternating e.m.f. are given in Plate I. Oscillograph No. 1 was taken with the molybdenite rectifier adjusted to give practically perfect rectification. No. 2 is with the same rectifier slightly out of adjustment (overloaded), so that the rectification is less perfect. No. 3 is with the same rectifier further out of adjustment. No. 4 is an oscillographic record with the carborundum rectifier. No. 5 is with the rectifier of brookite. In taking No. 2 the rectifier was submerged in oil, to test the effect of cooling.

Three Exposures. — In making these pictures the following steps were taken: The drum carrying the film was set rotating. The high-potential current obtained from Professor Trowbridge's 40,000 volt storage battery was started in the tube. The potential *V* (Fig. 128) and the contact of the rectifier were adjusted so that the deflection of the luminescent spot on the fluorescent screen showed good rectification. Exposure of about 2 minutes was then made. This exposure gave the heavy line of the oscillograms.

The switch at *T* (Fig. 128) was then thrown open, so that no current was flowing in the electromagnets and the luminescent spot came to its zero position. The exposure in this position was made for a shorter time of about 40 seconds. This traced a thin straight line along the centre of the picture and gave the axis of zero current.

The switch at *T* was then thrown to the position to put the resistance *R* in the circuit in place of the crystal. The resistance *R* had been previously adjusted, so that the amplitude of the deflection with *R* in the circuit should be equal to the maximum am-

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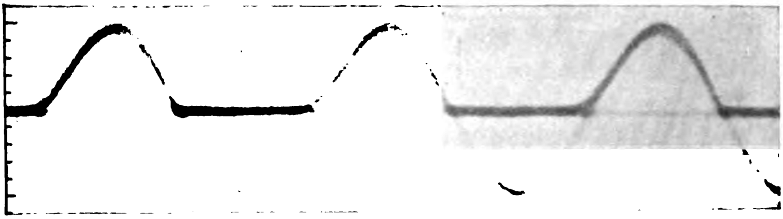

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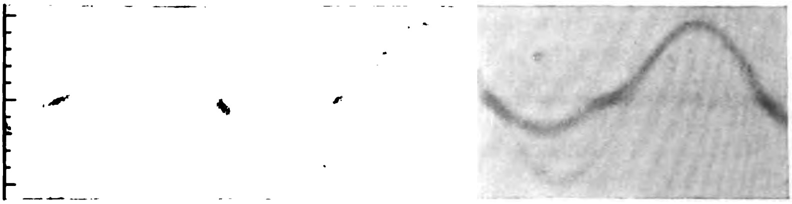

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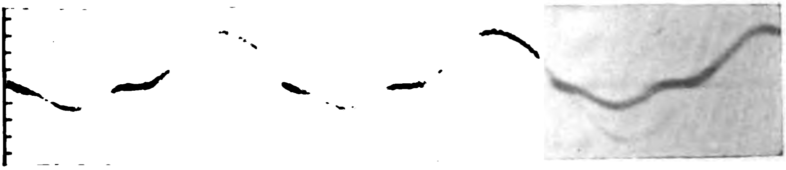

PLATE I. G. W. Pierce, Crystal Rectifiers.

plitude with the crystal in the circuit. With the resistance *R* in circuit an exposure of about 1 minute was made, giving the light sinusoidal curve of the picture.

On each picture the three exposures give, therefore, (1) the form of the rectified cycle as a heavy line, (2) the position of the axis of zero current, as a straight line through the figure, and (3) the form and position of the alternating current cycle when an equivalent resistance *R* is substituted for the rectifier. The last named cycle appears in the pictures as a thin-lined sine curve. This curve is in phase with the impressed voltage immediately about the crystal, and is referred to below as the "voltage-phase curve."

TABLE VI

TABULAR DESCRIPTION OF THE OSCILLOGRAPHIC RECORDS OF PLATE I

No.	Material of Rectifier.	Condition.	Maximum Rectified Current in Milliamperes.	R. M. S. Alternating Volts.	Equivalent Resistance in Ohms.
1	Molybdenite	Good adjustment	4.9	3.54	400
2	”	Out of best adjustment, submerged in oil and overloaded	4.9	3.54	400
3	”	Out of best adjustment	4.5		
4	Carborundum platinized on one side	Overloaded	5.4	22.0	6000
5	Brookite	”	3.0	2.22	992

Coördinates. — In tracing all the curves, the motion of the light spot over the paper is from left to right; the time coördinate is, therefore, horizontal and is drawn as usual from left to right.

The scale drawn in ink at the left-hand margin of each picture gives the value of the current, one division being one milliampere.

Conditions. — A tabular description of the conditions under which each of the records was taken is contained in Table VI.

A discussion of the records follows:

Oscillogram Nos. 1, 2, and 3 — Molybdenite. — The pressure of the copper rod against the molybdenite for good rectification is slight and is somewhat difficult to attain. Some points of the crystal are more sensitive than others, and the crystal has to be moved around under the copper contact and tried at several different points before the best adjustment can be found. Oscillogram No. 1 was taken with a molybdenite rectifier in good adjustment. The rectification in this case is seen to be practically perfect; the cycle through the specimen consists of a nearly sinusoidal curve for one half-period and a practically straight line for the other half-period. The large current flows from the copper to the molybdenite, and the zero current from the molybdenite to the copper.

When the pressure on the contact was increased until a small negative current was permitted to pass, oscillogram No. 2 was obtained. Increasing the pressure still more, so as to get a larger negative current, gave oscillogram No. 3.

One object in taking these oscillograms, together with the voltage-phase cycle, was to see if there is any evidence of lag of the rectified cycle with respect to the voltage-phase cycle. *No such lag* appears. On the other hand, the rectified cycles *lead* their respective voltage-phase cycles at three positions:

The first of these positions of lead is at the part of the cycle in which the rectified current approaches the zero axis after having traversed the upper half of the curve. This advance, which is so small as to be just perceptible in the oscillograms, amounts to about $\frac{1}{8000}$ of a second.

A second, somewhat larger, lead of the rectified cycle ahead of the voltage-phase cycle is at the point of rising from the axis after the rectified current has followed for a half-period along the zero axis. The lead here is about $\frac{1}{1500}$ second.

A third, very significant, lead of the rectified cycle is at the negative maximum, as is seen in the cases of imperfect rectification, oscillograms Nos. 2 and 3. Here the lead is a considerable fraction of a half-period.

Oscillogram No. 4 — Carborundum. — Oscillogram No. 4 was obtained with a carborundum rectifier consisting of a specimen of carborundum platinized on one side and held in a clamp under a contact pressure of 3 kg. When sufficient current was sent through the carborundum to give deflections suitable for the oscillogram, the carborundum was overloaded, and permitted the current to pass also in the negative direction. The carborundum cycle differs from the molybdenite cycle in the absence of a lead at the negative maximum and at the point of rising from the zero axis. This anomaly in the case of the carborundum rectifier is seen later to be the effect of its high resistance.

Oscillogram No. 5 — Brookite. — The form of the cycle obtained in this case is intermediate between the carborundum cycle and the cycle of oscillogram No. 3. This is consistent with the value of its resistance.

In order to investigate the meaning of the lead of the rectified cycles in the several cases, the oscillograms had to be examined mathematically with the aid of the theory of alternating currents.

Only the conclusions from this mathematical examination are here given. The mathematical reader is referred to the original paper.[1]

Conclusions from an Examination of the Rectified Cycle with the Aid of Alternating Current Theory. — (1) The case of the advance of the rectified cycle on rising from the axis of no current is shown in the mathematical discussion, above referred to, to be due to the fact that after a dormant half-period the current in the circuit follows the ordinary exponential " building-up " curve for a time before coming into coincidence with the sine curve. This building-up curve starts from the axis with zero lag, and is, therefore, in advance of the sine curve. It is chiefly due to the self-inductance in the oscillographic circuits. To this effect of self-inductance is to be added the effect due to the higher resistance of the rectifier for small currents than for large currents. This higher resistance brings the building-up curve a little nearer to the sine curve.

(2) The slightly quicker descent of the rectified cycle on approaching the axis after having traversed the upper half of the curve is also due to this higher resistance of the rectifier when traversed by smaller currents.

(3) The very significant lead of the negative maximum ahead of the corresponding voltage-phase maximum is explicable on the assumption that the rectifier has a much higher resistance in the negative direction than in the positive direction. We have shown in the mathematical discussion that the angle of lag of the voltage-phase cycle behind the impressed voltage, determined by the

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[1] G. W. Pierce: Physical Review, 1909, Vol. 28, p. 153; or Proc. Am. Acad. of Arts and Sciences, 1909, Vol. 45, p. 317.

inductance and resistance of the circuit, is

$$\tan^{-1}\frac{584}{836} = 35°,$$

while in the negative direction, to give proper amplitude, the substituted equivalent resistance should be at least 6470 + 436 = 6906 ohms, whence the angle of lag in this case would be

$$\tan^{-1}\frac{584}{6906} = 4.8°.$$

Therefore, the angle of lead of the rectified cycle ahead of the voltage-phase cycle, determined as the difference of these two angles of lag, is 30.2°. This value agrees with the oscillogram No. 2, for which the calculation was made.

In this connection it is interesting to notice that a lead of this negative maximum in the case of the carborundum oscillograph does not appear. The explanation of this is easily obtained if one substitutes for the resistance values of the molybdenite the corresponding values for the circuit containing the carborundum rectifier. The equivalent resistance of the carborundum in its positive loop is 6000 ohms, so that the angle of lag of the voltage-phase cycle with this resistance in it is only 5.6°, while in the negative direction the equivalent resistance of the carborundum is about 20,000 ohms, giving an angle of lag in the neighborhood of 1°. The difference between these two angles of lag, which would give the phase difference between the carborundum cycle and the corresponding voltage-phase cycle, would be a quantity just perceptible on the oscillogram, as was verified in the original photographs.

In conclusion of this discussion of the oscillograms, I should say that we have not been able to detect in the photographs any departure in amplitude or in phase between the rectified cycle and the voltage-phase cycle that is not accounted for by the inductance and resistance of the oscillographic apparatus or by the current-voltage curves of the rectifier.

This means that if there are any terms contingent upon heating or other effects which involve an integral of a function of the current with respect to the time, this integral attains its final value in a time within the limit of error of measuring the oscillograms, which is about 1/6000 second. This result contrasts with the result obtained in an oscillographic study of the electrolytic detector, where an integrative action was discovered (see next chapter).

THERMOELECTRIC PROPERTIES OF MOLYBDENITE

In the present section an account is given of the investigation of the thermoelectromotive force of molybdenite against copper and a determination of the temperature coefficient of resistance of molybdenite. Apart from their possible bearing on the action of the rectifier, the thermoelectric properties of molybdenite are of interest in themselves.

Thermoelectromotive Force. — Five specimens were mounted for the study of the thermoelectromotive force of molybdenite against copper. These specimens are referred to as "A," "B," "C," "D," and "E." The method of mounting the specimen *E* is shown in Fig. 129. A thin sheet of molybdenite .1 or .2 mm. thick, 2 cm. wide, and 8 cm. long, was cemented between two glass microscope slides *G* with a cement made of water-glass and calcium carbonate. The molybdenite was then copper-plated over a small area at each of the exposed ends *MM*, and to these copper-plated areas were soldered copper wires .2 mm. in diameter, so as to form

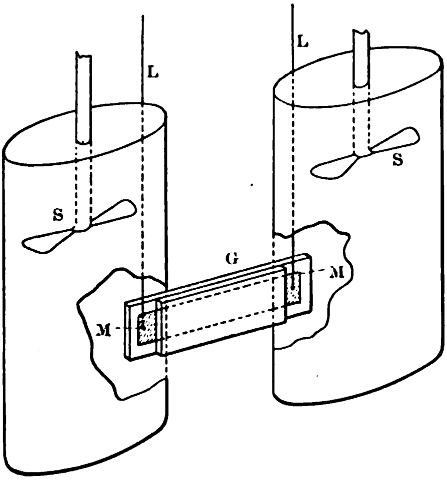

Fig. 129. Apparatus for studying thermoelectric properties of molybdenite.

thermal junctions with the molybdenite. The thermal junctions and the ends of the glass mounting were inserted into two brass vessels for containing the temperature baths of oil. The joints between the brass vessel and the glass mounting were made tight with the cement of water-glass and calcium carbonate. The oil baths were provided with stirrers driven by a motor. One of the baths was kept at 0° C., and the other bath was given various temperatures between 0 and 200° C. The resulting thermoelectromotive force was measured by means of a potentiometer to which the copper wires *LL* led. The results for the specimen "E" are recorded in Table VII and plotted in the curve of Fig. 130.

TABLE VII

THERMOELECTROMOTIVE FORCE OF THE COPPER-MOLYBDENITE COUPLE "E," THE COLD JUNCTION BEING KEPT AT ZERO

Temperature of Hot Junction.	E.M.F. in Millivolts.	Temperature of Hot Junction.	E.M.F. in Millivolts.
10.1	− 7.5	99.2	− 68.4
14.3	−10.7	109.3	− 75.2
16.2	−11.5	111.6	− 77.2
18.7	−13.8	116.3	− 79.2
21.5	−16.0	118.7	− 83.2
24.1	−17.6	133.2	− 90.7
25.6	−18.5	141.9	− 96.9
33.1	−24.6	156.8	−106.8
36.2	−25.9	166.9	−113.2
41.9	−31.5	176.8	−119.0
51.1	−36.7	179.0	−120.0
59.2	−42.5	180.9	−121.5
67.4	−48.6	188.5	−126.2
70.8	−51.2	192.7	−128.7
76.0	−54.1	195.0	−130.0
80.8	−57.2		

The negative sign before the e.m.f. in the second and fourth columns of Table VII indicates that this specimen of molybdenite is thermoelectrically *negative* with respect to copper; that is to say, the current at the hot junction flows from the molybdenite to copper.

In a similar way the other four specimens " A," " B," " C," and "D" gave the values recorded in Table VIII and plotted in Fig. 131. For the purposes of comparison a part of the curve obtained for " E " is also plotted in Fig. 131.

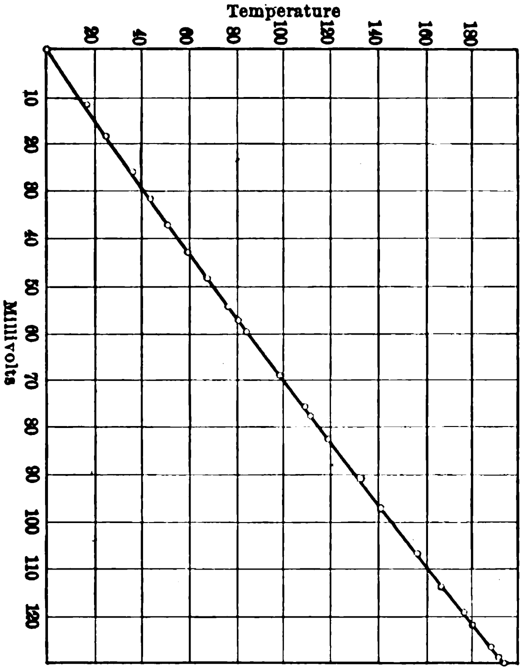

FIG. 130. Curve of thermoelectromotive force of molybdenite (specimen *E*) against copper, for various temperatures of the hot junction.

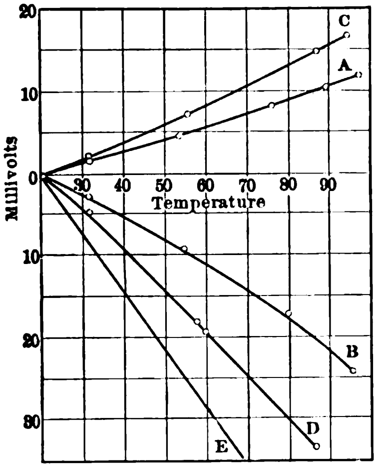

FIG. 131. Thermoelectric curves of various specimens of molybdenite against copper.

Some of the specimens (*B*, *D*, and *E*) are thermoelectrically negative with respect to copper, while the other specimens (*A* and *C*) are thermoelectrically positive with respect to copper. The thermoelectromotive force per degree differs largely with the different specimens, as may be seen by a reference to Table IX, which contains the thermoelectromotive force per degree of the different specimens of molybdenite against copper and against lead (obtained from the known value of the lead-copper junction). For comparison Table IX also gives the thermoelectromotive power of some other remarkable thermoelectric elements.

The comparison shows that these specimens of molybdenite have very large thermoelectromotive force against copper or against lead. The specimens *D* and *E* were found to be at the extreme negative end of the thermoelectric series.

The great variability among the specimens studied may be due to an admixture of small quantities of some other substance with the molybdenite, or it may be due to structural differences from point to point of the crystal. The differences in the specimens could not have arisen from the copper-plating or from the heat employed in soldering the junctions, because the specimens *A*, *B*, *C*, and *D* were tested before the copper-plating and soldering was done, and by means of the preliminary test were classified as positive, negative, positive and negative respectively, which agrees with the determination after soldering.

TABLE VIII

MOLYBDENITE-COPPER JUNCTIONS A, B, C, D. THE COLD JUNCTION WAS AT 20° C. THE HOT JUNCTION WAS AT TEMPERATURE T° C. THE THERMOELECTROMOTIVE FORCE V IS IN MILLIVOLTS

Junction A.		Junction B.		Junction C.		Junction D.	
T.	V.	T.	V.	T.	V.	T.	V.
31.9	1.45	31.6	− 2.70	31.7	2.01	31.6	− 4.81
53.5	4.63	54.1	− 9.21	55.2	7.20	57.5	−17.9
76.6	8.21	80.0	−17.1	87.2	14.9	59.8	−19.4
89.4	10.4	87.4	−20.0	94.4	16.6	86.7	−33.7
97.1	11.5	95.3	−24.2				

The preliminary test was made by touching the specimens with two copper wires attached respectively to the two terminals of a galvanometer, one of the wires being slightly warmer than the other. *This preliminary test proved very interesting in that it showed that one may find all over many of the pieces cut from a crystal of molybdenite points where the substance is thermoelectrically positive and other points where it is thermoelectrically negative.* These positive and negative points sometimes lie so near together that with a fine-pointed exploring electrode attached to a galvanometer and warmed by heat conducted from the hand, one may find the deflections of the galvanometer reversed from large positive values to large negative values on making the slightest possible motion of the pointer over the crystal.

Explorations of this kind failed to show any definite orientation of the thermoelectric quality with respect to the crystallographic axes.

The existence of small thermoelectrically positive and negative patches in a piece of the molybdenite may indicate that the thermoelectromotive force measured by attaching wires to the specimen is too low on account of the inclusion under the electrodes of both positive and negative areas which would partially neutralize the thermoelectric action against another electrode.

TABLE IX

Substance.	Thermoelectromotive Force in Microvolts, per Degree Centigrade, at 20° C.		Authority.
	Against Copper.	Against Lead.	
Molybdenite A	110	113	Present experiment
" B	−230	−227	"
" C	175	178	"
" D	−415	−413	"
" E	−720	−717	"
Silicon		−400	Frances G. Wick[1]
Bismuth		− 89	Matthiessen[2]
Antimony		26	"
Tellurium		502	"
Selenium		807	"

[1] Phys. Rev., 25, 390. [2] Everett, Units and Physical Constants.

It may be said in passing that the specimens D and E, *with soldered connections*, still showed the phenomenon of rectification when used with alternating currents, even when the two junctions of the copper with the molybdenite were in oil baths at the same temperature as the room and the oil in the baths was vigorously stirred with motor-driven stirrers. The rectification in this case was, however, very imperfect.

Temperature Coefficient of Resistance. — Another interesting thermal property of the molybdenite is its temperature coefficient of resistance. A brief report of this coefficient is here given.

Two specimens of the molybdenite were made into the form of resistance thermometers by depositing heavy copper-plated areas near the two ends of thin pieces of the molybdenite and soldering thin copper strips to the copper plate. For insulation a thin strip of mica was placed over the molybdenite, and one of the copper leads was bent back over the mica so that both leads ran away parallel with the mica insulation between. The whole conductor was then placed between two mica strips and inserted in a flattened brass tube. The tube was then mashed tight together so as to clamp securely the molybdenite and its leads. The end of the tube adjacent to the molybdenite was soldered up. The leads were brought out at the other end of the tube and connected to binding posts insulated by a hard-rubber head from the tube.

The two molybdenite resistances thus mounted are called No. 50 and No. 51. The molybdenite in No. 51 was .65 cm. wide by .7 cm. long; the thickness was about .3 mm.

The resistances of these two conductors were measured at various temperatures with the aid of a Wheatstone bridge. They showed no evidence of rectification. The values plotted in Fig. 132 were obtained. The curves marked " 50 " and " 51 " give the resistances of No. 50 and No. 51 respectively. The ordinates for these curves are at the left margin of the diagram, and are in ohms. The curves " C 50 " and " C 51 " are for the reciprocals of the resistance of No. 50 and No. 51 respectively. The ordinates for these curves are at the right-hand margin of the diagram.

Each of the specimens has a large negative temperature coefficient of resistance. With No. 50, for example, the resistance at 93.1° C. is 229 ohms; at 0° C. the resistance is 561 ohms; at − 76° the resistance is 3051 ohms; and at the temperature of liquid air the resistance of this specimen was found to be over 6,000,000 ohms. This last value is not plotted on the curves.

It is interesting to note that between − 15° *and* 93° *the temperature-conductance curve of each of the specimens is a straight line.*

At 0° C. the resistance of each of the specimens decreases about 1.53 percent per degree centigrade increase of temperature; at

20° the decrease of resistance per degree increase of temperature is 1.19 percent.

Plausibility of Thermoelectric Explanation. — The large thermoelectromotive force of the molybdenite against the common metals, together with its large negative temperature coefficient of resistance, lends plausibility to the hypothesis that the rectification is due to thermoelectricity. For if we pass an electric current through the rectifier and the current begins to make its way through a small area at the contact, this small area is heated and decreases in resistance, so that the greater part of the current flows through this particular small area, heating it still more, while the portions of the contact through which the current has not started remain cool and continue to offer a high resistance. The effect of this action is to confine the heating to an extremely small area, which is the condition necessary for the extremely rapid and efficient action of the rectifier, on the hypothesis of a thermoelectric explanation. That there is, however, an insuperable ob-

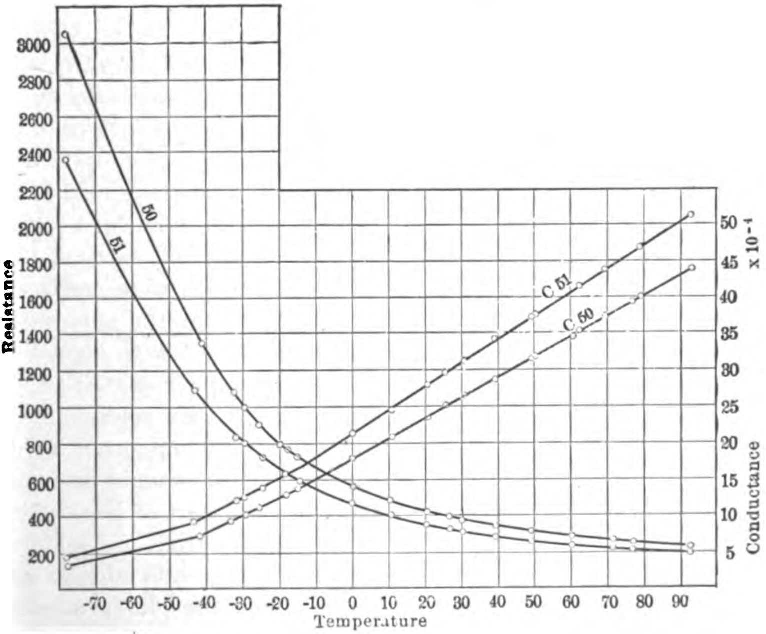

FIG. 132. Resistance and conductance of molybdenite as a function of the temperature.

jection to this explanation of the phenomenon is, I think, made clear in the succeeding experiments, in which it is shown that the thermoelectric effect is often opposite to the rectification, and that the amount of heat associated with the rectification accounts for less than $\frac{1}{300000}$ of the rectified current as thermoelectric.

EXPERIMENTAL FACTS ADVERSE TO THE THERMOELECTRIC EXPLANATION OF THE PHENOMENON OF RECTIFICATION

Thermoelectric Effect Opposite to the Rectification. — A number of experiments with different specimens of molybdenite were made in which the rectification and the thermoelectric effect could be simultaneously studied. A diagram of the arrangement of apparatus is given in Figure 133. The specimen of molybdenite is shown at *M*, and was held down upon a wooden base by a spring clip. One end of each of the specimens, which were easily interchangeable in the apparatus, was electroplated with copper at *S*. To this copper-plated area a copper lead was soldered. A copper rod *C*, supported as in Figure 124, was brought into contact with the part of the molybdenite distant from the soldered junction. The molybdenite and the contact were put in an electric circuit containing a galvanometer at *A* and a source of variable alternating potential at *V*. The alternating potential *V* could be applied or omitted by closing or opening the switch at *T*. A small heating coil was wound on the rod *C*, and another similar heating coil was wound on a second copper rod *E* placed immediately below the contact of *C* with *M*.

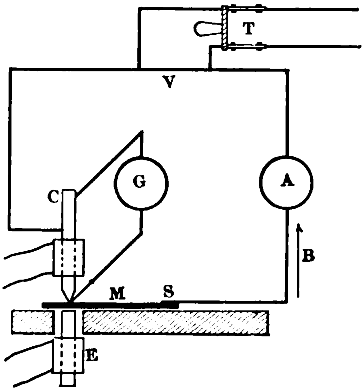

FIG. 133. Apparatus for comparing rectified current with thermoelectric effect.

An auxiliary thermal junction formed by a small constantan wire attached to the lower end of the copper rod *C* was connected to a second galvanometer shown at *G*, for use in a later experiment.

The copper rods *C* or *E* could be heated by the surrounding coils, and the thermal current in the circuit through the molybdenite or the circuit through the constantan could be read on the galvanometers A or G. Also the rectified current obtained by applying the alternating voltage V could be read on the galvanometer A. When the thermal current or the rectified current through A is in the direction of the arrow B, the molybdenite, following the usage in thermoelectricity, is said to be *positive.* When the current in A is in the direction opposite to the arrow B, the molybdenite is said to be *negative.*

The results obtained with a number of specimens of molybdenite when heat was applied *above,* and when heat was applied *below,* and when the *alternating voltage* was applied, are contained in Table X.

TABLE X

SIGN OF MOLYBDENITE WHEN HEATED ABOVE OR BELOW AND WHEN SUBJECTED TO ALTERNATING VOLTAGE

Specimen No.	Heated Above.	Heated Below.	Under Alternating Voltage.
75	+	−	−
81	+	−	−
Turned over	+	−	−
93	−	+	+
Another point	−	−	+
"	−	−	+
Turned over	−	−	+
78	+	+	+
Another point	+	−	−
"	+	+	−
94	−	−	+
Another point	−	+	+
"	−	+	+

From this table it appears that the thermoelectric voltage *when the junction is heated by heat conducted from above,* in twelve out of the thirteen cases tried, is opposite to the direct voltage obtained when an alternating current is passed through the junction. *When the heat is conducted to the junction from below, through the molybdenite,* the thermoelectromotive force in four cases is opposite to the rectified voltage, and in nine cases is in the same direction as the rectified voltage. In only one case, one point of No. 78, is the rectified voltage in the same direction as the thermal voltage, both when the junction is heated from above and when it is heated from below.

In all of these cases the heat was applied in the neighborhood of the same junction, and there is no opportunity for heat to get to the other junction (copper-plated and soldered) by conduction, on account of the great distance of the other junction from the source of heat. To make this absolutely certain this distant junction was in some cases submerged in an oil bath.

So far as I have been able to learn, this phenomenon of the reversal of the thermoelectromotive force at a thermal junction, conditioned on whether the heat is conducted to the junction through one element of the junction or the other element of the junction, is novel. It may be explained by the assumption of another thermal junction of opposite sign in the molybdenite itself below and in the immediate neighborhood of the copper-molybdenite junction. This assumption is plausible because it has been shown above that the molybdenite with which these experiments were performed is thermoelectrically an extremely heterogeneous substance.

However, whatever the explanation of the dependence of the sign of the thermoelectromotive force on the manner of applying the heat, it is seen that the thermoelectric effect is usually opposite in sign[1] to the rectified effect.

By applying heat from above and at the same time applying the alternating voltage, one can make the thermal current and the rectified current neutralize each other. This opposition of sign of the rectified current and the thermal current renders the correctness of the thermoelectric explanation of the phenomenon of rectification extremely improbable.

Insufficient Heating of the Contact to Account for Rectification. — The most convincing experiment on the subject is the following: With the aid of the auxiliary thermal junction of copper-constantan placed at the contact of the copper with the molybdenite, as shown in Fig. 133, it was possible to look for a rise of temperature of the copper molybdenite junction by the alternating current which was being rectified. If any appreciable heat were developed at the molybdenite copper junction, the copper-constantan junction ought to show it. The following result was obtained:

When the rectified current was 118 microamperes, the heating shown by the copper-constantan junction did not exceed .01° C.

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[1] In the case of silicon-steel, carbon-steel, and tellurium-aluminum, L. W. Austin has found that the rectified current generally flows in opposite direction to that produced by heating the junction. In his experiments (Bulletin of the Bureau of Standards, 5, No. 1, August, 1908) the heat was applied by conduction from above only.

When, on the other hand, as a control experiment, heat was applied to the copper-molybdenite junction from below so that it had to be conducted through the molybdenite and through the copper-molybdenite junction to get to the copper-constantan junction, the heating shown by the auxiliary copper-constantan junction was 11.4° C., while the thermal current from the copper-molybdenite junction was only .2 microamperes. In both the case of the rectified current and the case of the application of heat from below the heat had to be conducted from the point of rectification to the auxiliary junction. Therefore, with a rise of temperature of the auxiliary junction 1100 times as great as the rise shown during the rectification, the thermal current in the copper-molybdenite circuit was $\frac{1}{500}$ of the rectified current; that is to say, the rectified current, for a rise of temperature of $\frac{1}{100}$ of a degree of the auxiliary junction (being approximately a linear function of the temperature) was less than $\frac{1}{500000}$ of the rectified current from an alternating current producing the same rise of temperature.

Summary of Conclusions from the Experiments with the Crystal Rectifiers. — 1. An examination of the characteristics of contact detectors using carborundum, anatase, brookite, hessite, iron pyrites, and silicon shows that we are dealing with the same kind of phenomenon in the case of all these crystal substances. The various other crystal-contact detectors which I have not examined probably act in the same way.

2. At the contact between the crystal and a common metal, or between two different crystals, or between two apparently similar crystals, there is asymmetric conductivity, permitting a much greater current to flow in one direction than in the other under the same applied voltage.

3. These contacts all have a rising current-voltage characteristic.

4. These crystals all have a large thermoelectromotive force against the common metals, and the amount and the direction of this thermoelectromotive force is different at different points on the crystalline bodies.

5. The rectifying effect is also different in amount and direction at different points of the crystalline body; the direction of the rectifying effect is often opposite to the effect that would be obtained by heating the contact.

6. Thermoelectricity does not explain the phenomenon of rectification, but the two effects, since both exist in such marked

degree in the same bodies, may be related in that both may have their seat in some common property of the materials employed. *For example, if we suppose that a surface of separation between the crystalline body and some other body permits the passage of electrons more easily in one direction than in the other, this would account for the rectifying effect, and would also account for the thermoelectric effect, provided the velocity of the electrons is suitably different at different temperatures.*

7. The thermoelectric explanation of the rectifying effect, if we had found it to be supported by the experiments, would have correlated the phenomenon of rectification at a solid contact with the body of information that we already have in regard to thermoelectricity, but we should still have had by no means a complete knowledge of the action, because our understanding of thermoelectricity is very incomplete.

8. From experiments with thermoelectricity we are familiar with the fact that the energy of an oscillatory electric current passing through a high-resistance contact is partially converted into heat energy, and that the heat energy so obtained, if produced at a thermal junction, is again partially converted into electric energy manifesting itself as a direct current. It is perhaps, after all, more simple to suppose the alternating current to be converted into direct current without the intermediation of heat; and this seems to be the case with the crystal-contact rectifiers. This result opens up a new field for investigation, which may contribute to a better understanding, not only of thermal electricity, but of the much larger question of the mechanism of electrical conductivity in solid bodies.

CHAPTER XIX

ON DETECTORS (*Concluded*)

THE ELECTROLYTIC DETECTOR, AND VACUUM DETECTORS

Description of the Electrolytic Detector. — The electrolytic detector for electric waves, as described by Fessenden [1] and shortly after by Schloemilch,[2] consists of a cell containing an electrolyte and having one electrode of very small area, usually in the form of an extremely fine wire of platinum, and as the other electrode a larger area of platinum or some other metal. When used in wireless telegraphy the two electrodes are connected in a circuit upon which the electric oscillations are impressed, so that the rapidly oscillating electric currents in the circuit are made to traverse the cell of the detector. An example of a simple form of receiving circuit, with the detector connected in the antenna, is shown at *MDG* of Fig. 134. A local circuit *TED*, through the detector, contains a telephone receiver *T* and an adjustable source of e.m.f., which is used to polarize the detector by sending through it and the telephone a small direct current. Under the action of the electric oscillations through the detector the current in the telephone receiver is modified so as to produce a sound in the telephone with a period determined by the train frequency of the incident electric waves. The action is localized at the contact of the fine wire with the electrolyte.

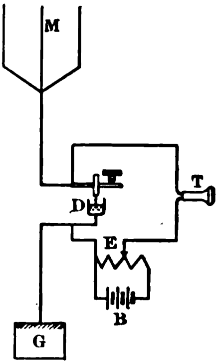

FIG. 134. Circuit with electrolytic detector.

Details of the Electrolytic Detector. — The electrolyte employed in the electrolytic detector is usually 20% nitric acid, though almost any electrolytically conductive liquid (e.g., dilute sulphuric acid, common salt solution, caustic soda, etc.) may be used. For a highly sensitive detector the fine platinum wire employed as

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[1] Fessenden, U. S. Patent, No. 727,331, filed April 9, 1903; issued May 5, 1903.

[2] Schloemilch, Elektrotechnische Zeitschrift, Vol. 24, p. 959, Nov. 19, 1903.

the sensitive " point " may be as small as one or two ten-thousandths of an inch in diameter. For a less sensitive detector, which is not so likely to be destroyed by strong signals, wire as large as one-thousandth of an inch or even larger may be used.

Only a very short length of the fine wire comes into contact with the electrolyte; for the fine wire is either sealed into a glass tube so as to protect all but the mere end of the wire from contact with the electrolyte, or the fine silver-coated platinum wire, as at *W*, Fig. 136, is carried up or down by a micrometer adjustment so as to bring it into contact with the electrolyte. The silver is removed from about $\frac{1}{10}$ of an inch of length of the wire by submerging it in the electrolyte, which is in this case nitric acid, and sending a current from the local battery through it for a few minutes, *with the small wire as anode.* This takes off the silver, leaving the bare platinum. The point, so formed, is then withdrawn by a motion of the screw *B*, until only a very minute area of the bare platinum wire is left in contact with the electrolyte.

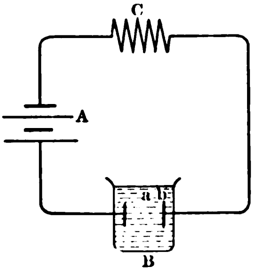

Fig. 135. Professor Pupin's electrolytic rectifier.

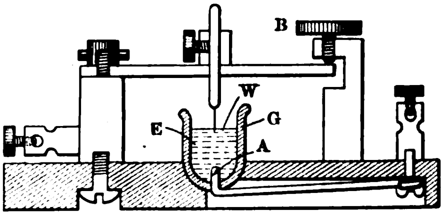

Fig. 136. Electrolytic detector with adjustable contact.

The detector in this form is used with an adjustable source of e.m.f. in its local circuit. The fine platinum electrode may be connected either to the positive or the negative terminal of the battery, but the detector is usually more sensitive when this fine platinum electrode is positive (i.e., anode). The voltage in the local circuit required in this case is about 1.5 volts.

Variation in which Source of Polarizing Voltage is Located in the Detector Itself. — Instead of employing an external voltage *E* (Fig. 134) to polarize the detector, a similar effect can be obtained by constituting the electrodes in the detector of different metals, one of which (zinc, say) is attacked by the electrolyte, and the other of which, the fine platinum wire, is inert to the action of the electrolyte.

This makes the detector itself a primary battery.

This arrangement for which a United States patent has been issued to Schloemilch,[1] and also to Shoemaker,[2] would seem to be incapable of the high sensitiveness attained by the form in which the accurately adjustable external voltage, as in Fig. 134, is employed.

Regarding the Theory of the Electrolytic Detector. — Considerable diversity of opinion has been expressed by various writers as to the manner in which the electrolytic detector acts as a receiver for electric waves. Professor Fessenden in his original patent attributes the action to heat, and he calls this form of detector a "liquid barretter." Professor Armagnat,[3] who has made an experimental study of the subject, attributes the action to a rectifying effect resulting from polarization. Armagnat obtained a curve of the form of Fig. 137 for the current-voltage characteristic of the electrolytic detector. Dr. L. W. Austin [4] also found that the electrolytic detector acted as a rectifier for small alternating currents, but came to the opinion that heat, chemical action, rectification, and electrostatic attraction across the gas film might have a part in the explanation of the phenomenon when the detector was used with electric waves.

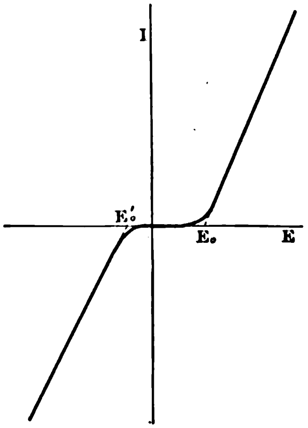

FIG. 137. Current-voltage curve of electrolytic detector.

A doubt that arose in the minds of some investigators of the subject as to a possible explanation of the phenomenon in terms of rectification alone came, it seems, from the idea that there could not be energy enough in the electric waves received at great distances to produce the effects in any other way than by a triggering action, by which the local energy of the battery was

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[1] Wilhelm Schloemilch, U. S. Patent, No. 936,258, filed Oct. 3, 1903, issued Oct. 5, 1909.

[2] Harry Shoemaker, U. S. Patent, No. 795,312, filed Feb. 13, 1905, issued July 25, 1905.

[3] Armagnat, Bul. soc. française, session of April, 1906, p. 205; Journal de Physique, Vol. 5, p. 748, 1906.

[4] Austin, Bul. Bureau of Standards, Vol. 2, p. 261, 1906.

brought prominently into play. Now, however, since some of the crystal detectors, that act entirely without any local source of energy, are as sensitive as the electrolytic detector, we see that the energy to produce the sounds in the telephone is really present in the incoming waves, and does produce the sounds when the incoming energy is applied to the telephone receiver with the aid of a suitable rectifier.

The Electrolytic Detector as a Rectifier. — That an electrolytic cell with one of the electrodes small, when suitably polarized with a direct current, is a rectifier for alternating currents was first shown by Professor M. I. Pupin[1] before such a cell came into commercial use as a detector for electric waves. The following account of Pupin's rectifier is translated from an article published in the "Jahrbuch der Elektrochemie," Vol. 6, p. 35, 1899:

"In Fig. 3" (here reproduced as Fig. 135) "*A* is a battery, *B* an electrolytic cell with the platinum electrodes *a* and *b* and acidulated water. If the polarization of the cell *B* is as great as the e.m.f. of *A*, no current flows in the circuit. If one allows an alternating current to act upon the circuit *ABC*, the circuit contains resistance, self-inductance, and a capacity localized in the plates *a* and *b*. The cell *B* acts, however, as a condenser only so long as the potential difference of the plates *a* and *b* is smaller than the decomposition voltage. If this value is exceeded, a current goes through the circuit. If the alternating current, for example, has an amplitude that is twice as great as the e.m.f. of *A*, in case the phase has the same direction as *A* a current flows in the circuit, e.g., in the direction *BC*; when the phase is oppositely directed, the condenser *B* sends a current in the opposite direction. This last can be diminished by making the capacity of *B* very small. If, for example, the area of one of the electrodes is only one square millimeter, one may easily rectify alternating currents with a frequency of 1000 per second; with greater frequency the electrode must naturally be made still smaller. It is best to employ a platinum wire sealed into glass — the wire being cut off immediately at the end of the glass. The author (Pupin) succeeded in rectifying electric oscillations of Hertzian frequency and producing electrolytic effects with them; the wire for this purpose was .025 mm. in diameter."

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[1] Pupin, Electrical World, Vol. 34, p. 743, 1899; Zeitsch. f. Elektrochemie, Vol. 6, p. 349, 1899; Jahrbuch d. Elektrochemie, Vol. 6, p. 35, 1899; Bul. Am. Phys. Soc., Vol. 1, p. 21, 1900.

This quotation shows that Pupin had employed the electrolytic detector in 1899 as a rectifier for electric waves of Hertzian frequency, and that he had a well-defined explanation of the processes occurring in the rectifier. I have made some experiments that fall into close agreement with Pupin's explanation of the phenomenon. These are described in the succeeding paragraphs.

OSCILLOGRAPHIC STUDY OF THE ELECTROLYTIC DETECTOR[1]

In these experiments the current through the detector under the action of an alternating e.m.f., superposed on a polarizing current, is determined by means of an oscillograph. The application of the oscillograph to the problem gives the instantaneous values of the current through the detector, and permits an examination of the wave form of the rectified cycle. The oscillographic apparatus was the Braun's tube described in Chapter XVIII.

Circuits Employed with the Detector in Taking the Oscillograms. — The electrolytic detector used in these experiments made use of a platinum point, .0002 inch in diameter, dipping into 20 per cent nitric acid, and was adjusted to high sensitiveness as an electric wave detector immediately before taking the oscillograms. A diagram of the circuits employed in the experiment, together with a sketch of the oscillographic apparatus, is shown in Fig. 138.

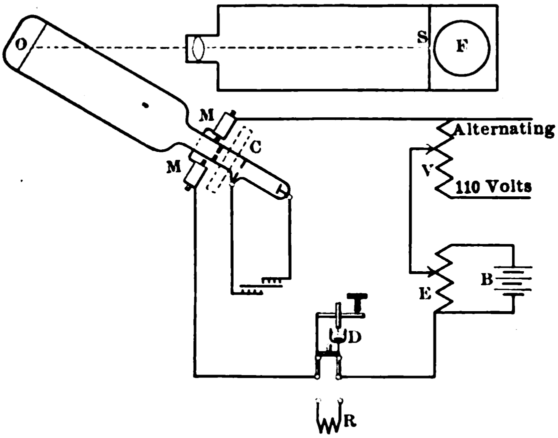

FIG. 138. Oscillographic apparatus and circuits for study of electrolytic detector.

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[1] This account is an abridgment of an article by the author on "The Electrolytic Detector, Studied with the Aid of an Oscillograph." Physical Review, 1909, Vol. 28, p. 56.

The detector is at D, and is connected in series with the deflecting coils MM of the oscillograph and with the variable sources of voltage V and E. The voltage V is taken from a potentiometer connected with the 60-cycle alternating mains of the laboratory. E is an adjustable steady voltage taken from a battery. The voltage at E could be reversed. By opening the switch near D the electrolytic detector could be disconnected from the circuit, and by throwing this switch downward an ohmic resistance R could be substituted for the detector.

In taking the oscillograms of Plate II the following steps were employed: The drum carrying the film was set rotating. The high potential current was started in the tube. The chosen value of the polarizing current was applied to the circuit and was read on a direct-current milliammeter. The alternating current was superposed on the circuit, and by adjustment of the potentiometer at V the voltage of this alternating current was given any desired value.

The Exposures. — After the preliminary adjustment of the direct and alternating currents through the detector, four exposures were made on each picture, while the film was being carried around continuously by the synchronously driven drum.

Axis of Zero Current. — This is the lower straight line across the pictures, and was obtained by an exposure of 20 seconds taken with the circuit open.

Axis of Polarizing Current. — This is the upper straight line across the picture, and was obtained with the detector in circuit and traversed by the polarizing current. The exposure was 20 seconds. In oscillogram No. 1 this axis is not apparent, because on account of the small value of the polarized current employed it falls into coincidence with the axis of zero current.

The Rectified Cycle. — This cycle may be identified in the oscillograms as a positive[1] loop for a half-period, followed by a nearly straight portion lying along the axis of zero current for a part of a half-cycle, and going over into the positive loop through an intermediate " building up " segment. This cycle (exposure of 60 sec.) was taken with the detector in circuit, with the alternating e.m.f. applied to the circuit, and with the polarizing current also flowing.

The Voltage-Phase Cycle. — This is the sine curve of the pictures, and was taken in order to obtain the e.m.f. immediately

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[1] In describing the oscillograms, values *above* the axis of zero current are called positive; values below this axis are called negative.

about the detector.[1] A similar curve was made use of in the experiments of the preceding chapter and is there discussed. In the present experiments, because of the employment of the polarizing current with the rectifier, a question arises as to the appropriate method of taking this cycle. Two different methods were tried, either of which, by proper elimination of the constants of the oscillographic apparatus, will give the desired result. The method yielding simplest results for the voltage-phase cycle is the following: After the exposure for the rectified cycle had been made, the alternating voltage was left unchanged, and a resistance was substituted for the rectifier. A double adjustment of the substituted resistance and the direct voltage was made by successive approximations until the result was attained that (1) the direct voltage alone gave through the substituted resistance a current equal to that used in polarizing the rectifier and (2) the alternating voltage superposed on this direct current gave a deflection of the luminescent spot to a point coincident with the maximum point attained with the rectifier in the circuit. This means that the voltage-phase cycle was taken with the axis of polarizing current as axis, and with amplitude equal to the maximum amplitude of the rectified cycle. This method was employed in oscillograms 1, 2, and 5.

The second method of taking the voltage-phase cycle was as follows: The polarizing voltage was reduced to zero, the detector was short-circuited, and an alternating voltage equal to that used with the detector was applied to the circuit. This method was employed in oscillograms 3 and 4.

Coördinates of the Oscillographic Curves. — In taking all of the curves of the oscillograms, the motion of the light spot over the film is from left to right; the time coördinate is, therefore, the horizontal scale of the curves and is drawn as usual from left to right. The current coördinate is given in the scale drawn in ink at the left-hand margin of each picture — one division being one milliampere.

DISCUSSION OF THE OSCILLOGRAMS OF PLATE II

The oscillograms shown in Plate II are reproductions of positives printed from the films carried by the rotating drum. They were taken with a 60-cycle alternating current applied to the circuit

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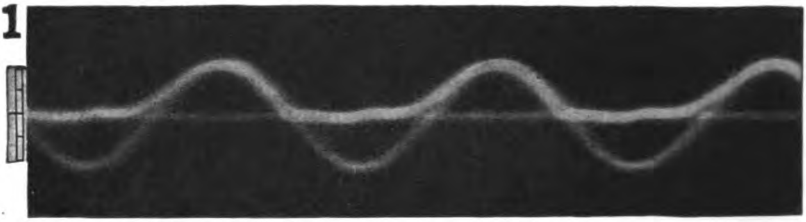
[1] The ordinary method, which would be to take the leads from the two sides of the detector through a high resistance to the oscillograph, could not be used because the oscillograph was working at the limit of its sensitiveness on the full voltage without the added resistance.

1



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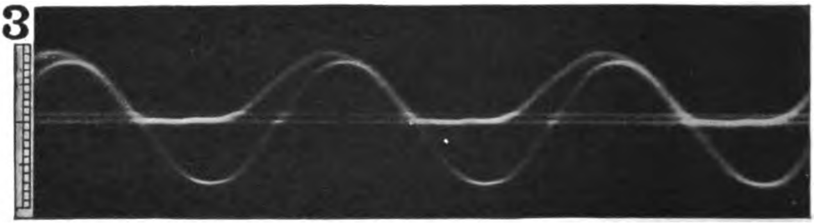

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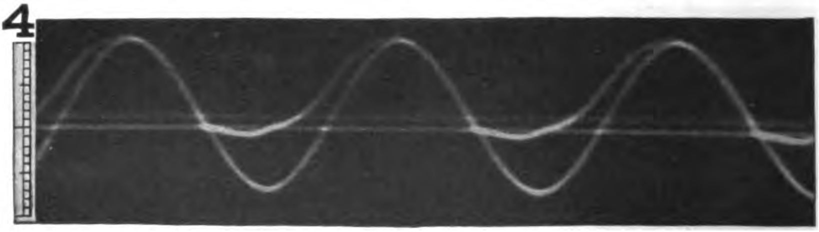

5

PLATE II. G. W. Pierce, The Electrolytic Detector.

containing the electrolytic detector. The reproduction is one-third the size of the original. The several curves shown in the plate were obtained with different polarizing currents superposed on the circuit. Table XI contains a tabulation of the polarizing current and voltage, the applied alternating voltage, the maximum current through the detector, and the substituted resistance employed in taking the voltage curve.

TABLE XI

TABULAR DESCRIPTION OF THE OSCILLOGRAPHIC RECORDS

No.	Polarizing Direct Current in Milliamperes.	Polarizing E.M.F. in Volts.	R.M.S. Volts A.C.	Maximum Positive Current through Detector in Milliamperes.	Equivalent Resistance in Ohms.
1[1]	.1	1.45	2.09	2.37	440[1]
2	1.0	5.5	4.00	9.6	70
3[2]	1.2	5.5	4.00	9.6	00[2]
4[2]	1.4	Not measured	5.00	10.0	00[2]
5	2.2	”	5.00	11.0	150

[1] It should be noticed that the sensitiveness of the oscillograph when No. 1 was taken was three times as great as when the other oscillograms of the plate were taken.

[2] The voltage-phase cycle of oscillograms 3 and 4 was taken with the polarizing current omitted, so that they have the axis of no current as axis of the cycle.

Point Anode or Cathode — the Large Loop in the Direction of the Polarizing Current. — Some of the oscillograms were taken with the polarizing current from the point to the electrolyte and some with the polarizing current in the opposite direction. Although the values of the polarizing voltage required to produce a given polarizing current were different in the two cases the general characteristics of the cycle were the same. A reversal of the polarizing current reversed the rectified current, and whether the polarizing current was from the point to electrolyte or in the opposite direction the large loop of the rectified cycle (always oscillographed positively) was obtained when the alternating current was flowing in the same direction as the polarizing current.

The Form of the Rectified Cycle. — The cycle obtained with the rectifier in the circuit has the same general form in all the pictures. When the current, having traversed the positive loop, comes to the axis of zero current, it follows along this axis for a short way, then takes a small negative dip, becomes positive again, follows along just above the axis of zero current for a short time, and then rises along a transition curve to the positive loop.

Calculations Concerning the Form of the Cycle. — The rectified cycle, when examined by comparison with the voltage-phase cycle, makes a misleading impression unless one takes carefully into account the condition under which the curves are obtained. One must bear in mind that the form of the current through any rectifier is not determined by the rectifier alone, but is a function also of the constants of the circuits employed with the rectifier. In the present experiments the deflecting coils of the oscillographic apparatus possessed appreciable self-inductance and resistance, and these factors must be taken into account.

Taking these factors into account, by a mathematical investigation not here given I have obtained the following results for oscillogram No. 2. The applied alternating e.m.f. is represented by the dotted curve of Fig. 139, with volts at right-hand margin. The resulting voltage-phase curve calculated from this e.m.f. and the constants of the circuit is displaced 38° to the right from the e.m.f. curve and is given by the continuous-line sine curve. The rectified cycle, calculated approximately from the current-voltage characteristic of the detector and the applied voltage gives a curve of the form of the heavy line in Fig. 4. This calculation accounts for the general form of the rectified cycle and its relation to the voltage-phase cycle. The electrolytic detector has an important peculiarity, which is shown by the oscillogram, and to which attention is now directed.

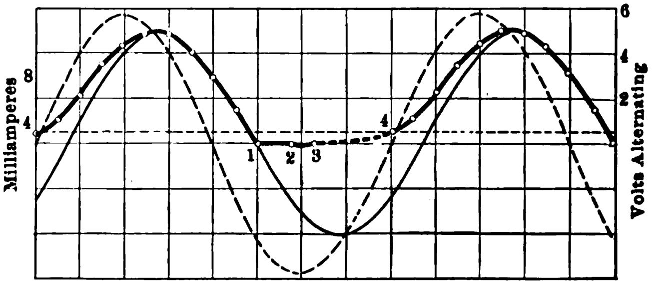

FIG. 139. Computed curves.

Evidence of Polarization Capacity. — On oscillograms 1, 2 and 3 there is a small positive rise of the photographic curves in the region to the immediate right of the negative maximum. This rise is more striking in the original photographs than in the reproductions; and, though small, it deserves attention, because the occurrence of this small positive maximum is evidence of the existence for about $\frac{1}{1500}$ of a second of a positive e.m.f. greater than the e.m.f. immediately following. Now in this part of the cycle the externally applied e.m.f. is greater following the rise than during the rise; therefore the rise indicates the existence of a positive e.m.f. in the circuit itself. This is capable of the following explanation in terms of the theory of polarization. After the prevalent external e.m.f. has been in a negative direction and has returned to zero, the polarization tension which has been opposing the negative current at the electrode continues to exist for a short time and produces a positive current. This action, resembling that of a capacity, is familiarly known as the *polarization capacity* of the electrode. By the existence of the small positive maximum near the axis of the cycle, the oscillogram shows that the polarization capacity of the electrode is not entirely negligible. Evidence of the existence of this polarization capacity is clearly given by the oscillograms 1, 2, and 3. The oscillograms 4 and 5, while not having a positive maximum near the axis, show also a striking tendency toward a maximum at this point, which is, however, masked by the rapid rise of the building-up curve in this part of the cycle.

CONCLUSIONS IN REGARD TO THE ELECTROLYTIC DETECTOR

1. The whole phenomenon of the rectification of small alternating currents by the electrolytic detector seems to be explicable in terms of the theory of electrolytic polarization.
2. The polarization capacity of the small platinum electrode is not entirely negligible, even with currents making only 60 cycles per second. The polarization capacity may, however, aid in producing a rectified current as well as in opposing this effect, and apart from the effect of this capacity on the tuning of the circuit, does not detract from the utility of the rectifier as a detector for electric waves.
3. The present conclusions in regard to the action of the detector are entirely in accord with Pupin's original brief description of the phenomenon as quoted above.

COMPARISON OF THE ELECTROLYTIC DETECTOR WITH THE CRYSTAL RECTIFIERS

The resemblance of the oscillograms with the electrolytic detector to those with the crystal rectifiers [1] is close, in so far as depends on the fact that both classes of rectifiers are nearly perfect [2] rectifiers when employed under their best conditions. The electrolytic rectifier, in order to approximate perfection [3] as a rectifier, must be polarized by the superposition of a direct current; while the use of the direct current with the crystal rectifier, does not always materially improve the rectification. Also *the two rectifiers are different, in that the electrolytic rectifier shows evidence of electrolytic polarization capacity, which, so far as may be judged from the oscillograms, is absent with the crystal rectifier.* The experiment with the electrolytic detector, since it shows in the matter of polarization capacity the integrative action of this detector, which was sought for and not found with the crystal rectifier, is thus an interesting "control" experiment.

In the matter of sensitiveness the best crystal rectifiers are about equal to the electrolytic detector.

VACUUM DETECTOR

Another highly sensitive detector, by which the electrical oscillations at a wireless telegraph receiving station are rectified and detected, makes use of the unilateral conductivity of a vacuous space containing electrons produced by an incandescent body. A rectifier for electric oscillations making use of this principle, invented by Professor J. A. Fleming,[4] and called by him an "oscillation valve" is represented in Fig. 140. In this figure *a* is a glass bulb, a little smaller than an ordinary incandescent lamp bulb; *b* is a carbon filament, like that of an incandescent lamp, which is heated to incandescence by connection through the leads *f* and *e* with a battery *h*. Surrounding the filament but not touching it is a metallic cylinder *c*. The bulb is pumped to a high degree of exhaustion. When the filament is raised to incandescence by a

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[1] Pierce, Part II., *l. c.*

[2] A rectifier is called "nearly perfect" when the ratio of the current in one direction to that in the opposite direction is large.

[3] The current through the electrolytic rectifier is slightly asymmetric when no polarizing current is employed.

[4] Proc. Roy. Soc. London, 1905, Vol. 74, p. 476; also U. S. Patent, No. 803,684, filed April 19, 1905, issued Nov. 7, 1905.

current through it, negative electrons are sent off from it and render the space between the filament and the cylinder conductive for an electric current, provided the e.m.f. producing this current is directed from the cylinder to the hot filament. In case the e.m.f. is applied in the opposite direction, no current, or a much smaller current, flows. An oscillating e.m.f. applied to the cylinder and filament produces more current in one direction than in the opposite direction.

One method of connecting the valve into a wireless telegraph receiving circuit is shown in the diagram, which is taken from Professor Fleming's U. S. Patent Specifications. Here the valve is in a circuit connected inductively with a wireless telegraph antenna. Electrical oscillations in the antenna induce an oscillating electromotive force in the coil *k*, and this oscillating e.m.f. sends more current in one direction than in the opposite direction through the valve and through the current-indicating instrument *l*.

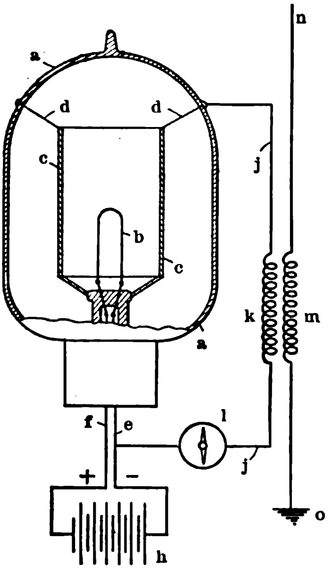

FIG. 140. Professor Fleming's vacuum tube rectifier.

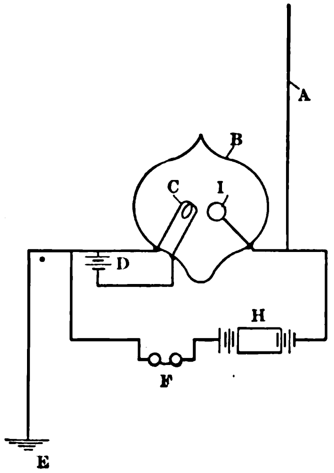

FIG. 141. Circuit employed by Dr. DeForest with vacuum detector.

A modification of the method of connecting the indicating instrument to the *oscillation valve* has been made by DeForest so as to permit the use of a telephone as indicator. A diagram of a circuit of this form taken from DeForest's U. S. Patent Specifications [1] is shown in Fig. 141, in which F represents a telephone receiver and H a battery connected in the local circuit through the vacuum rectifier B (which Dr. DeForest calls an *audion*).

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[1] See U. S. Patent, No. 836,070, filed Jan. 18, 1906, divided May 19, 1906, issued Nov. 13, 1906.

CHAPTER XX

ELECTRICAL RESONANCE

WAVE METERS. RESONANCE IN SIMPLE CONDENSER CIRCUITS

On account of the multiplicity of facts requiring presentation in an elementary discussion of electric wave phenomena, it is often difficult to decide what is the most direct course to follow. For a part of the way, in the earlier chapters, we were able to proceed almost in the historic order. Up to about the year 1900, the growth of knowledge of electric waves, so far as pertains to wireless telegraphy, occurred as a fairly direct sequence of important events, which have been sketched in Chapters I to XIII. About the year 1900 the literature of the subject began to multiply enormously and practical progress began to develop in many directions. Two main branches of this development we have already pursued, in a discussion of the propagation of the electric waves to long distances over the surface of the earth and in a discussion of some of the detectors used in receiving the signals. We shall now begin the study of a third main branch of the subject; namely, Electrical Resonance.

Introduction to a Study of Electrical Resonance. — In previous chapters attention has been called to the importance of bringing different parts of the sending and receiving circuits into resonance with one another. By this means the strength of the signals is increased, and the interference arising when several stations are operated simultaneously is partially eliminated.

The main elements of variation in attuning circuits one to another are inductance and capacity. Preparatory to the study of more complex cases of resonance, let us recall the experiments of Sir Oliver Lodge, described in Chapter VIII, in which two Leyden-jar circuits were attuned to each other. One of the Leyden-jar circuits, which I shall call the oscillating circuit, was provided with a spark gap, and was charged by an electric machine and allowed to discharge. The other Leyden-jar circuit (compare Fig. 142) was at a distance of perhaps a meter or two from the oscillating circuit, and could be adjusted as to period of vibration by a variation of its self-inductance by means of the slider $C'D'$. When brought into resonance by adjusting its period to that of the oscillation circuit, this second circuit was thrown into a violent state of electrical oscillation which might even break through the glass of the receiving Leyden jar unless provision for preventing this were made by providing it with a spark gap in shunt with the jar.

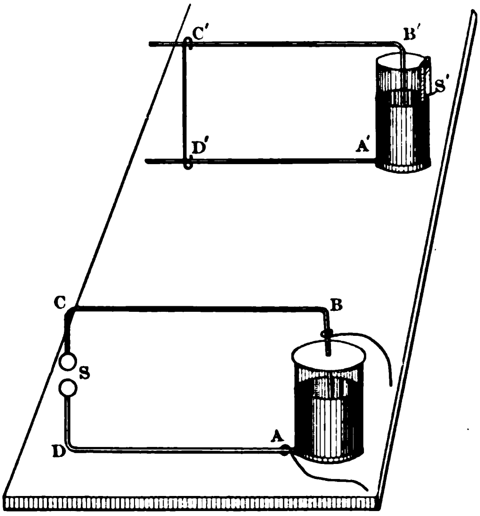

Fig. 142. Lodge's resonant circuits.

The presence of a maximum sparking across this gap served to indicate that the jars were in resonance.

Drude's Use of Lodge's Resonant Receiving Circuit for Determining the Period of the Oscillating Circuit. — In 1902 Professor Paul Drude[1] published a description of a resonant method for determining the period of an oscillatory condenser discharge. Drude used an apparatus in every way similar to Lodge's receiving circuit, with, however, capacity and inductance of such shape as to be easily calculable, and with a scale attached to the inductance, so that the period of the receiving circuit was known for any particular adjustment of the variable inductance. Such a calibrated receiving circuit is a *frequency meter* or a *wave meter*. Reference is made to Fig. 143. Suppose that it is required to determine the period of the oscillating circuit, shown as Circuit I. The frequency meter, shown as Circuit II, is brought up near the oscilla-

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[1] *Annalen der Physik*, Vol. 9, p. 611, 1902; see also Vol. 60, p. 17, 1897.

tory circuit, and by adjusting the slider S of Circuit II this circuit may be brought into resonance with the Circuit I of unknown period. The condition of resonance is indicated by the maximum glow in a sensitive vacuum tube in contact with one of the plates of the condenser of the frequency meter. When this resonant adjustment has been made, the position of the pointer P on the scale is read, and from this reading the period of the frequency meter is known, for by calculation Drude has calibrated the frequency meter in terms of the period corresponding to any particular adjustment of the pointer on the scale.

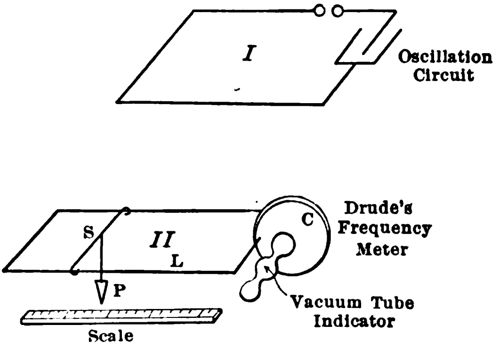

FIG. 143. Drude's resonant method of measuring wave-length and frequency.

The period of the frequency meter at resonance is the same as that of the oscillating circuit; which is, therefore, also known.

Likewise, the wave length in air that Circuit I emits is known, for this wave length is the velocity of light times the period.[1]

In terms of units,

Wave length in meters = $3 \times 10^8 \times$ period in seconds.

By means of this apparatus Drude was able to determine wave lengths between 2 and 445 meters.

Doenitz's Wave Meter. — Dr. Johann Doenitz[2] of Berlin, Germany, has constructed a wave meter that is in a very compact and convenient form for measuring the wave lengths of wireless telegraphy. Instead of a gradually variable inductance, as in Drude's apparatus, Doenitz's instrument has a gradually variable condenser

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[1] See Chapter X.

[2] *Elektrotechnische Zeitschrift*, Vol. 24, pp. 920–925, 1903. German Patent, No. 149,350, from April 4, 1903. U. S. Patent, No. 763,164, filed Sept. 15, 1903, issued June 21, 1904.

fb (Fig. 144). This variable condenser consists of two sets of semicircular plates, one fixed and the other movable by rotation on a vertical axis. The capacity of the condenser is thus changed by bringing a larger or smaller area of the two sets of plates into interlapping position. This is the condenser of Korda[1] described in Chapter XIV. The condenser is provided with a pointer passing over a scale *t*. This scale on the wave meter is calibrated directly in wave lengths.

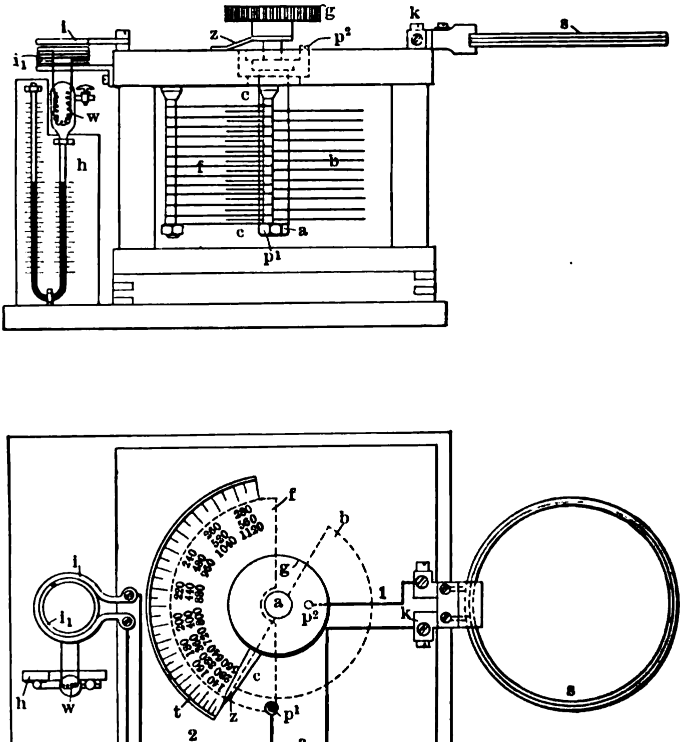

Fig. 144. Doenitz wave meter.

In series with the variable condenser is a loop of wire *s*, and another smaller loop *i*. When the instrument is brought up near an oscillating circuit so that the oscillations act inductively on the loop *s*, currents are induced in the wave-meter circuit, and these currents are the larger the nearer the period of the wave meter

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[1] Korda, German Patent, No. 72,447, issued Dec. 13, 1893.

approaches resonance with the oscillating circuit whose wave length is to be measured. Resonance is determined by noting the amount of current in the wave-meter circuit. This is done by means of a Harris or Riess hot-wire air thermometer *h*, which is, however, not connected directly into the wave meter circuit, but is coupled with it by means of the oscillation transformer $i\,i_1$. The action of this transformer and thermometer is as follows: The primary i of the transformer is in the wave-meter circuit; the secondary i_1 of the transformer is in series with a resistance w, designed to be heated by the current through it. This heating of the resistance heats a quantity of air in a glass bulb surrounding the resistance, causing this air to expand, and to push up a column of mercury in the bent tube *h*. As the wave meter approaches resonance with the oscillation circuit, the rise of the column of mercury in the bent tube increases.

By reading this indicator, not only can one determine the resonant adjustment of the wave-meter circuit, but one can also form some idea of the sharpness of resonance by noting whether small or large variations of the condenser are required for a given rise of the indicator.

The range of wave lengths measurable by Doenitz's wave meter is changed by substituting various coils of different numbers of turns for the receiving loop *s*. For each of the coils there is a corresponding calibration of the scale.

Sample of Observations Made with a Doenitz Wave Meter. — The curves of Fig. 145 were obtained[1] by a Doenitz wave meter. The curves show the scale reading of the air thermometer for various settings of the wave meter. Curve I was obtained by tuning the wave meter to an oscillating antenna circuit; Curve II was obtained by tuning the wave meter to an oscillating condenser circuit. The condenser circuit and the antenna circuit are seen to have the same wave length, 320 meters, indicated by the fact that this value, 320 meters, is the reading of the wave-meter scale when the thermometer scale reading is a maximum. Now when the two circuits of curves I and II were coupled together, and the wave meter applied to a study of the oscillations occurring in the coupled system, the results plotted in Curve III were obtained. The resonance curve in this case has two maxima. To this subject we shall return.

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[1] Figure 145 is copied with some slight modifications from Lieutenant-Commander S. S. Robison's Manual of Wireless Telegraphy, 1906.

Fleming's Wave Meter. — A wave meter devised by Professor Fleming,[1] and called by him a *cymometer*, is adjustable to resonance by gradual variation together of both the capacity and the inductance. A photograph of the instrument is shown in Fig. 146. The condenser consists of two concentric brass tubes *O* and *I*, separated by a vulcanite dielectric *V*. The variable inductance is a coil of wire *LM* wound on a tube of vulcanite, and is varied by a clip *K*, sliding over the bared wire of the coil. The electric oscillations to be measured act inductively on the receiving loop, consisting of the condenser *OI*, the inductance *LM*, and the wire *PQ*, which are in series. The clip *K* of the inductance, the tube *O* of the condenser, and the pointer passing over the scale *S* are moved together by the handle *H*, so that the capacity and the inductance of the instrument are increased or decreased together and almost uniformly along with the motion of the pointer. The condition of resonance is indicated by a maximum glow of a Geissler tube *G* attached to the terminals of the tubular condenser.

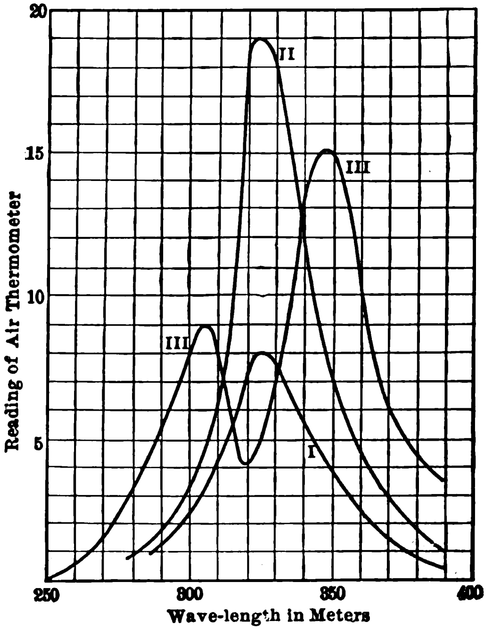

FIG. 145. Curves obtained with the Doenitz wave meter.

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[1] Fleming: The Principles of Electric Wave Telegraphy, p. 404. Longmans, 1906.

An advantage of Fleming's cymometer over other forms of wave meter arises in the fact that the scale readings are nearly proportional to the wave length (giving a nearly uniform scale when calibrated in wave lengths), whereas with instruments of the Doenitz type the wave length is nearly proportional to the square root[1] of the capacity of the adjustable condenser, so that the divisions on the scale become wider apart as the wave length increases.

Fleming's instrument has, however, the disadvantage of lack of compactness, for the inductance and condenser of this instrument are from one to two meters long.

Pierce Wave Meter. — I have designed a wave meter that has met with some use in practical application to wireless telegraphy. It consists of a Korda semicircular plate condenser C (Fig. 147), in series with a loop L for receiving the inductive action, and in series with a specially constructed high-frequency telephone receiver T. A pointer carried by the axle of the movable plates of the condenser passes over a scale, which is calibrated directly in wave lengths.

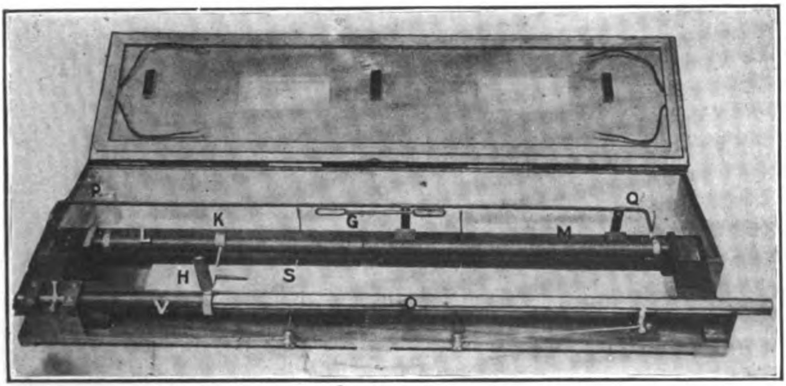

FIG. 146. Fleming cymometer.

At resonance, a maximum sound is produced in the high-frequency telephone receiver. On account of the high sensitiveness of the telephone receiver the wave length of currents in which the oscillations are extremely feeble may be determined, and also, on account of this high sensitiveness, the condenser can be made very compact and light, so that the whole instrument in the standard form weighs only 14 pounds.

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[1] This the reader may verify by examining the formula $\lambda = 2\pi v\sqrt{LC}$.

For extending the range of the instrument to long wave lengths, an inductance (to right of condenser) is included in the instrument and can be thrown in or out of circuit by the switch *S*.

Also the receptor loop *L* has a double rotation. One rotation is about an axis running from right to left in the picture, so that the loop can be placed parallel to any oscillating circuit; and the other rotation is about an axis perpendicular to the figure, so that the loop may be folded back over the pointer and inclosed in the cover of the instrument, as is shown in the lower cut of Fig. 147.

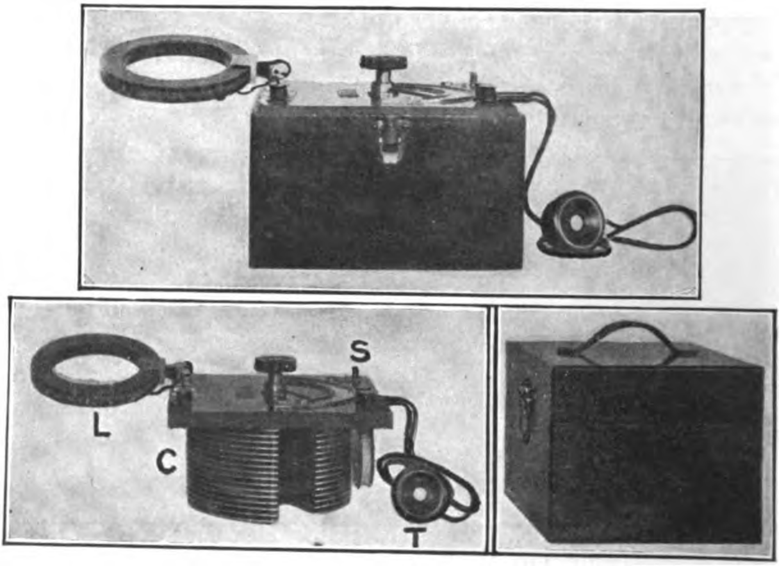

FIG. 147. Pierce wave meter.

Calibration of Wave Meters. — One method of calibrating a wave meter is by tuning it to resonance with various lengths of two parallel wires. This method, which we have already described, is applicable up to about 200 meters. For greater wave lengths the parallel-wire method is cumbersome, and, according to Diesselhorst, shows a systematic error, increasing with increase of wave length. With wave lengths above 200 meters I have employed the device of photographing the spark of a discharge circuit with the aid of a revolving mirror. The revolving mirror apparatus was like that of Fig. 4, with, however, the addition of an accurate device, called a "stroboscope," for determining the period of revolution of the mirror.

Having the period of revolution of the mirror and the distance between spark-terminal images on photographs like those of Fig. 3, one has a direct measurement of the period T of the discharge of a given oscillating circuit. By constructing a large number of such oscillatory discharge circuits giving various periods of discharge, or, better, by using a discharge circuit whose period could be varied at will, one may obtain accurate values of various periods by the use of the revolving mirror; and from the various periods T one can obtain the wave length λ in air of the emitted wave by the formula

$$\lambda = v \times T,$$

where $v = 3 \times 10^8$ meters per second, T is the time in seconds of one complete oscillation of the circuit, and λ is wave length in meters.

The wave meter to be calibrated is now set to resonance with each of these known wave lengths and the wave length is written at its appropriate position on the scale of the instrument.

Another method of calibrating a wave meter is by tuning it to resonance with circuits of which the period is known by calculation from a knowledge of capacity and inductance.

Method of Using a Wave Meter. — Let it be required to determine the wave length in air emitted by the oscillation circuit S, Fig. 148. The wave meter must be placed in such a position that the magnetic force from S links with the loop L of the wave meter; the oscillations in S then act inductively on the wave meter. This action is a maximum when the loop L is close up to S and in a plane parallel with it. It is, however, not advisable to have the two circuits too close together, because in this case the oscillations

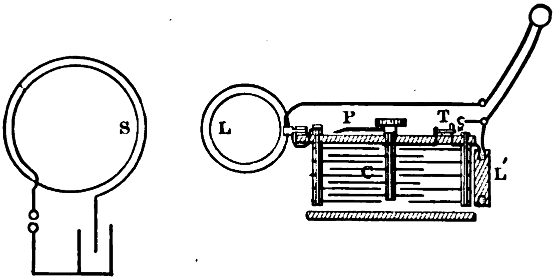

FIG. 148. Position of wave meter for determining the wave length or frequency of the circuit S.

induced in the wave-meter circuit react on the oscillating circuit and change its period.

With the wave meter in inductive relation to the discharge circuit, by adjusting the condenser of the wave meter, a maximum deflection is obtained in the hot-wire air thermometer in the case of the Doenitz wave meter. This deflection is a maximum when the wave meter is adjusted to resonance with the discharge circuit; and when this adjustment has been made the required wave length is read off directly on the calibrated scale.

With the use of the Fleming wave meter a maximum glow is obtained in the Geissler tube, at resonance, and the corresponding wave length is directly read.

With the Pierce wave meter a maximum sound is obtained in the high-frequency telephone, and the corresponding wave length is directly read.

Use of the Wave Meter in the Determination of the Capacity of the Discharge Condenser. — Professor Fleming has pointed out the utility of the wave meter in the determination of the capacity of a condenser. His method consists of discharging the condenser across a spark gap through a known inductance and measuring the wave length produced. He then calculates the capacity C by use of the formula

$$\lambda = v \cdot 2\pi \sqrt{LC},$$

where λ = wave length in meters measured by the wave meter, $v = 3 \times 10^8$ (the velocity of light in meters per second), and L = the known value of the inductance through which the discharge occurs.

A sample set of observations that I have taken in this way is shown in Table XII. The values of the inductance in the discharge circuit (see first column) were obtained by a bridge method.

TABLE XII

DETERMINATION OF CAPACITY BY THE WAVE METER. LEYDEN JAR NO. 45

Inductance in Discharge Circuit in Henrys.	Wave Length in Meters.	Capacity in Farads Computed by Thomson's Formula.
3.10×10^{-5}	690	$.00432 \times 10^{-6}$
4.90	865	.00432
6.61	1005	.00430
8.35	1130	.00432
10.0	1235	.00430
12.0	1345	.00427
14.05	1450	.00418
16.1	1560	.00423
		Mean, $.00428 \times 10^{-6} \pm 1$ per cent.

The last column contains eight independent determinations of the capacity with an average error of only 1%.

This is one of the best methods of determining the capacity of a condenser under conditions of actual use.

Effect of Resistance on the Sharpness of Resonance. — In tuning a condenser circuit with adjustable capacity or inductance to resonance with an oscillating circuit, as was done in the wave-metrical experiments above described, we have a simple case of the kind of tuning that is made use of at a receiving station when it is desired to receive signals of one wave length and exclude signals of a different wave length.

One of the main difficulties in completely excluding undesired signals arises from the fact that the detectors used in receiving the signals have a high resistance.

Let us see how the sharpness of resonance is affected by resistance of the receiving circuit, in the simple case in which a condenser circuit (e.g., the wave-meter circuit) is attuned to a given wave length.

As an example, I shall take a case in which the constants of the receiving circuit are within the range employed in wireless telegraphy. In Fig. 149 suppose that L is an inductance of .0001 henry, I an instrument for measuring the oscillatory current (root of mean square current) produced by an incoming electric wave, which is supposed to have a wave length $\lambda_1 = 300$ meters; C is a variable capacity, and this capacity is supposed to be calibrated directly in wave lengths, λ_2. Let the receiving circuit be set at various wave lengths and let the corresponding current be read on the instrument I.

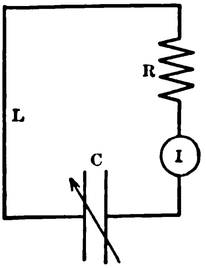

FIG. 149. Simple oscillation circuit.

By a calculation that is not here reproduced, it can be shown that the results plotted in Fig. 150 will be obtained. The relative current is plotted vertically, while the settings of the wave length of the receiving circuit divided by the wave length of the incident wave (λ_2/λ_1) are plotted horizontally.

The different curves in the diagram show the effects of putting different values of the resistance R into the receiving circuit. A maximum current is received in each case when $\lambda_2 = \lambda_1$, but the sharpness or flatness of the curves depends on the value of R. When $R = 628$ ohms the top curve is obtained. This curve is nearly flat, so that large changes in the period of the receiving circuit produce only small diminutions of the received current. Going successively to the values $R = 314, 207, 125, 63$, and 6.3 ohms, we get sharper and sharper resonance, shown by the curves corresponding to these values of R.

By a further examination of this set of curves we can see how well the receiving circuit with various values of resistance can discriminate between signals of different wave lengths coming at the same time. · Suppose, for example, with the 300 meter wave coming, we try to get a message of wave length 1.20 × 300 = 360 meters. If we have only 6.3 ohms in the receiving circuit, and set for 360 meters (1.2 in horizontal scale), we should get about 3% of current from the 300 meter wave along with the full value of the 360 meter wave. This would usually not cause any difficulty. If, on the other hand, our receiving circuit has a resistance of 63 ohms we should receive 33% of the 300 meter wave along with the 360 meter wave; and with a resistance of 628 ohms in the receiving circuit, we should receive 95% of the full current of the undesired 300 meter wave when we were in tune for the 360 meter wave.

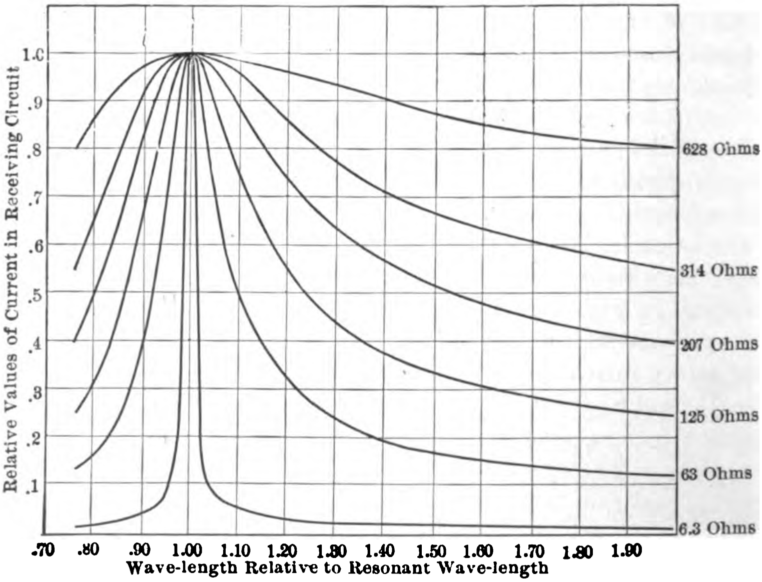

FIG. 150. Effect of resistance on sharpness of resonance, assuming a constant inductance of .0001 henry. Wave length varied by varying capacity.

In this problem I have supposed that the waves which are arriving are themselves undamped. If they also have strong damping, the interference would be a little greater than that described, but the main imperfections of tuning are due to the resistance of the receiving station and not to the lack of purity of the wave from the sending station. The illustration shows that we cannot get very sharp resonance so long as we have to use a high resistance (the detectors) in the particular receiving circuit here employed. This difficulty is, however, considerably reduced by the use of coupled circuits at the sending and receiving stations, in the place of the simple condenser circuit of this computation.

In the next chapter some facts in regard to resonance with coupled circuits will be presented.

CHAPTER XXI

ON RESONANCE (*Continued*)

ON THE ELECTRICAL OSCILLATIONS OF CONNECTED SYSTEMS OF CONDENSER CIRCUITS

HAVING briefly examined the conditions of resonance in simple condenser circuits, let us next consider the case of the coupled circuits involving principles that are now generally employed in sending and receiving the signals of wireless telegraphy and wireless telephony.

Reason for Using Coupled Sending Circuits. — The chief reason for the use of coupled circuits at the sending station is as follows: A closed condenser circuit is not a good radiator of electric energy, hence an antenna is employed for the purpose of radiating the energy. But on account of the comparatively small capacity of the antenna we cannot easily apply large amounts of power[1] directly to the antenna without using a very long spark gap in the antenna, so as to get the necessary high potential. Now the use of a long spark gap carries with it disadvantages; it does not produce good oscillations.

To avoid this disadvantage, the high potential in the antenna is obtained, not by the use of a long spark gap, but by the inductive action of a discharge occurring in a condenser circuit connected with the antenna and put into resonant relation with it, as shown in Figs. 151 and 152. The large amount of power in the condenser circuit is attained by the largeness of the capacity instead of by the length of the spark gap. By the use of a suitably large capacity in the condenser circuit we can obtain tremendous current in this circuit, which will induce very large potential in the antenna, if the antenna is in resonance with the condenser circuit. We thus get a large amount of radiation.

It is proposed to describe some experiments on the oscillations of connected systems of circuits. Attention is here chiefly confined to the sending station. The receiving station will be examined later.

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[1] $\text{Power} = \frac{\text{No. of charges per second} \times \text{Capacity} \times (\text{Maximum Potential})^2}{2}.$

Simplified Form of Circuits. — In order to simplify the conditions somewhat, in the present experiments, instead of employing the wireless telegraph circuits with the antenna constituting the capacity of the secondary circuit (such an antenna being in the form of a capacity distributed along a wire also possessing inductance), this antenna, for the purposes of these experiments, is replaced by a condenser, so as to have a localized capacity in

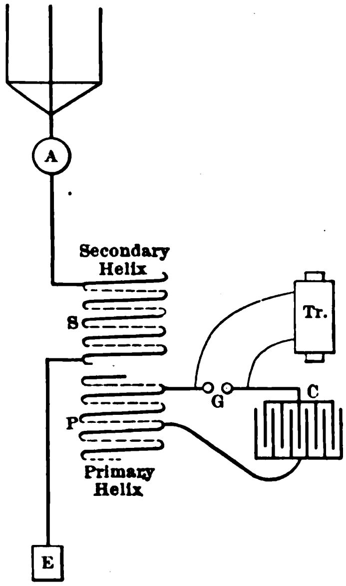

Fig. 151. Inductively coupled transmitting station.

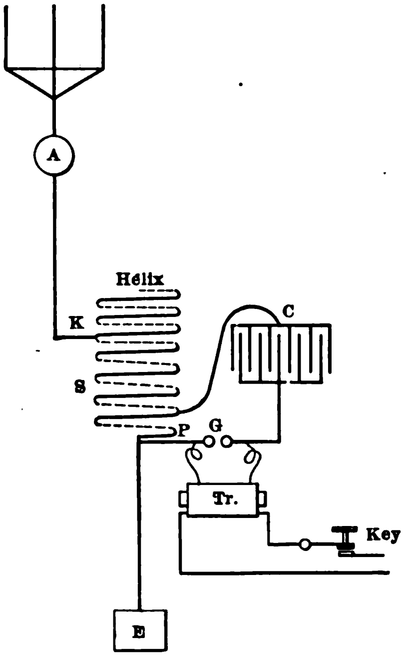

Fig. 152. Direct coupled transmitting station.

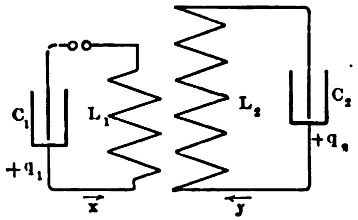

Fig. 153. Inductively coupled condenser circuits, with the antenna and ground of Fig. 151 replaced by a condenser.

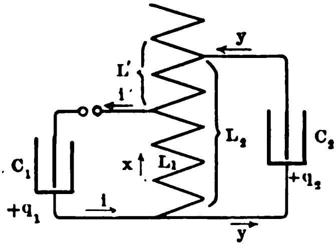

Fig. 154. Direct coupled condenser circuits.

each of the circuits. While this change does not simplify the experiments, it enables us to apply certain fairly simple theoretical formulas to the examination of the result. Without these formulas, we should have difficulty in seeing any interrelation among the results and the constants of the circuits used in the experiments.

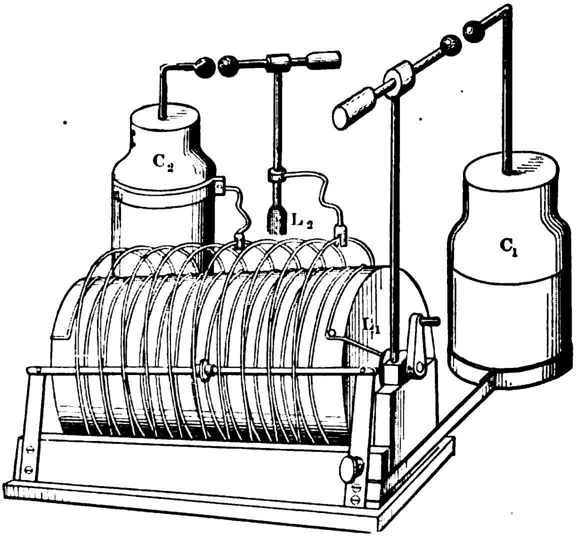

Fig. 155. Sketch of inductively connected condenser circuits.

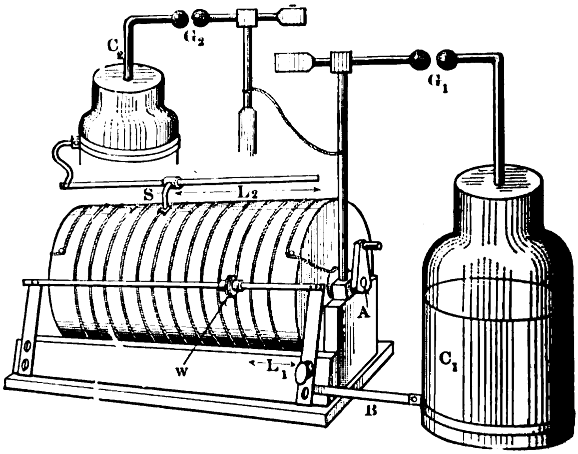

Fig. 156. Sketch of direct coupled condenser circuits.

Our simplified circuits are of the forms shown in diagram in Figs. 153 and 154 and in sketch in Figs. 155 and 156.

In Fig. 155, which represents the inductively connected system, two condensers C_1 and C_2 are connected to two coils L_1 and L_2, which are inductively related but insulated from each other. The number of active turns of wire on each of the coils may be varied; L_2 is varied by the clip contacts, and L_1 is varied by a wheel contact that may be moved along the inner spiral by a rotation of the drum on which the inner spiral is wound.

Each of the condenser circuits is provided with a spark gap, so that either circuit, when connected to a step-up transformer, may be used as the discharge circuit. The other circuit may then be looked upon as a secondary circuit. When the spark gap of the secondary is opened too wide to permit the passage of a spark, or, what is the same thing, when the secondary is removed, the period of oscillation is the period of the primary alone. When, on the other hand, the secondary is left in place and the spark gap of the secondary is closed (compare Fig. 153), the oscillations of the discharge circuit C_1 L_1 induce oscillations in the secondary circuit C_2 L_2, and we have a periodic flow of current in both circuits. It is proposed to give an account of some measurements of the wave length produced in the circuits when uncoupled and then when coupled with each other, and to compare the measured values with values computed from certain useful formulas.

In the *Direct Coupled System*, represented in Fig. 156, which was also studied, the transformer of the inductive coupling is replaced by an auto-transformer; that is, the two condensers C_1 and C_2 are made to discharge through parts of the same coil. In this case, also, both the inductances L_1 and L_2 can be varied independently by the motion of the contacts W and S. Also, both the condenser circuits are provided with spark gaps, so that either circuit may be caused to oscillate alone or to constitute the discharge circuit in a connected system with closed secondary.

These two forms of circuits, Figs. 155 and 156, are derived from the ordinary wireless telegraph circuits by replacing the antenna and ground of the wireless telegraph station by the two coatings of a condenser respectively. The circuits in these simplified forms will yield results that will aid in understanding the actual wireless telegraph circuits, which are to be examined in subsequent chapters.

Dimensions of the Inductances. — The coils employed in the apparatus shown in Figs. 155 and 156 had the following dimensions:

Coil.	No. Turns.	Diam. Wire.	Coil Diam.	Pitch.
Outer of Fig. 155	24	.208 cm.	18 cm.	.81 cm.
Inner of Fig. 155	51.5	.208	13	.42
Coil of Fig. 156	51.5	.208	13	.42

The inductances of various numbers of turns of these several coils were measured on a Rayleigh's bridge, and these values are recorded in the subsequent tables which contain the wave-length measurements.

General Statement of the Results. — Because of the difficulty of following the details of the experiments, I shall make at the outset a general statement as to the results.

When two circuits are coupled together, either *inductively* or *directly*, the primary circuit will have two periods of oscillation, and the secondary will have the same two periods of oscillation; and this is true, with a few exceptions, even when both of the circuits have been attuned to the same period before being coupled together. This double periodicity of the oscillation of the coupled circuits produces two distinct wave lengths, so that a coupled system emits two waves.

Also, the energy of the oscillation is at first all in the primary circuit, and gradually passes over into the secondary circuit, during which process the current in the primary becomes less and less with each vibration, while the current in the secondary becomes more and more with each vibration. After the energy has all gone into the secondary, the current in the primary becomes zero. Then the energy gradually comes back into the primary and the current in the secondary becomes zero. This process may repeat itself many times.

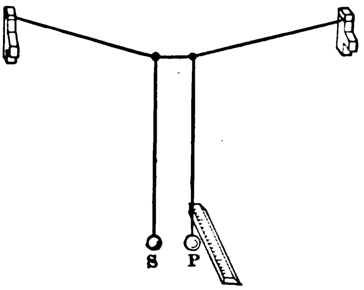

FIG. 157. Coupled pendulum.

Experiment with Sympathetic Pendulums. — As a digression, in order to see just how this takes place, the reader is asked to set up a simple apparatus like that shown in Fig. 157, which consists of two pendulums hung from a loosely suspended transverse cord about 3 feet long. This supporting cord may be tied to any two convenient objects; for example, the backs of two chairs. The pendulum bobs may be any two small bodies of about the same weight—two heavy nails will do. At first make the lengths of the threads supporting the two pendulum bobs the same. Now leave one of the bobs at rest, pull back the other in a direction at right angles to the plane of the strings, and then release it. Note what happens. Try the effect of making the cross cord tighter or looser, and also the effect of making the two pendulums of unequal length.

The vibratory motion of the pendulums represents very well the electrical vibratory motion that takes place with the coupled condenser circuits.

Oscillograms of the Pendulum Motion. — In order to show graphically the nature of the pendulum motion, I have elaborated the pendulum apparatus a little, and taken a moving picture (oscillogram) of the motion of each of the pendulum bobs. To do this, a camera was placed in the position shown at *C* in Fig. 158. At the back of the camera is a small horizontal slit *A*, and back of this slit is a sheet of bromide paper *F* carried by a rotating drum *D*. In order to have a bright object upon which to make the exposure, a small Nernst glower *G* was hung just above one of the pendulum bobs. This Nernst filament was put into an electric circuit by means of the small wire *W*, which also served as the suspension for the pendulum, and by means of the return wire *R*, which was carried up in such a manner as not to interfere with the freedom of motion of the pendulum. The current was started in the glower by heating it with a match while the current was on. As the pendulum swung, the image of the Nernst glower moved back and forth along the slit *A*. A small horizontally moving point of light thus entered the slit and fell upon the film. If now the sensitive

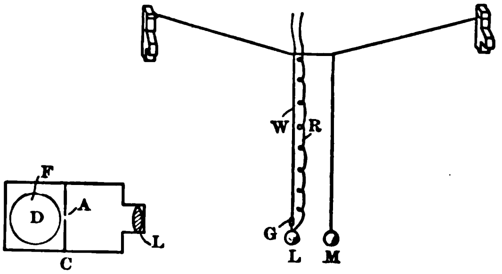

FIG. 158. Coupled pendulum with arrangement for photographing the motion.

paper is given a uniform motion by the rotation of the drum, the paper moves vertically past the slit, while the image of the swinging light moves horizontally along the slit. The combined effect of these two motions is a wavy line on the photographic paper. Four curves thus obtained are shown in Fig. 159. These curves

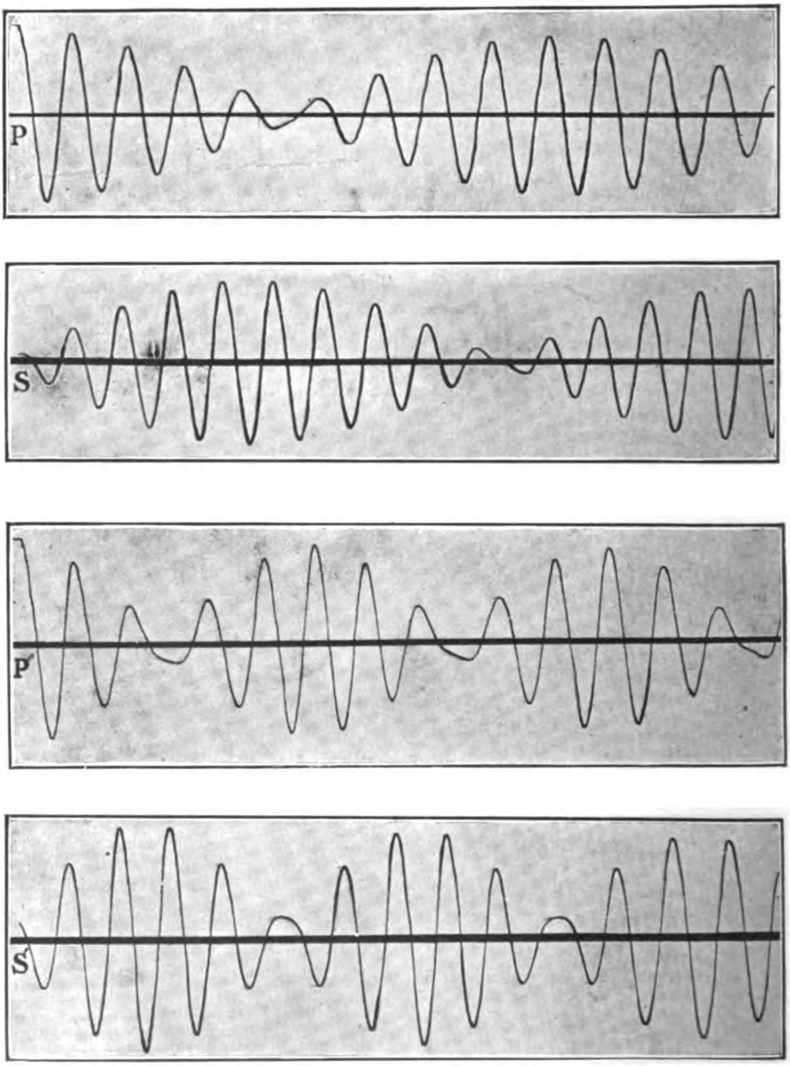

Fig. 159. Photographs of motion of the coupled pendulum.

show the displacement of the bob plotted vertically, against time plotted horizontally.

The first curve *P*, of Fig. 159, was obtained by leaving the ball *M* initially at rest, and pulling aside and releasing ball *L* (Fig. 158). The motion here corresponds to the primary current in the coupled condenser circuits. The second curve *S* was obtained by leaving the ball *L* initially at rest and releasing *M*. This curve corresponds to the secondary current of the coupled condenser circuit. The two cords supporting *L* and *M* were of the same length in the case of these two experiments.

As another experiment, the two cords were both equally shortened, and the transverse supporting cord was loosened; the curves *P'* and *S'* were obtained for the motion of the ball *L* initially displaced (primary) and initially at rest (secondary) respectively.

The curves *P* and *S* or *P'* and *S'* represent very well the electrical vibratory motion of the coupled condenser circuits, if we think of the displacement of the bob in the two curves as representing the current in the primary and secondary circuits of the coupled-condenser oscillation.

How the Curves Show the Existence of Two Periods. — Each of the curves of Fig. 159 shows the existence of two periods, in the motion of the pendulum, by the presence of "beats." If two vibrations of different periods coexist in the same system, the slower of these vibrations will fall more and more behind the other in phase until the two vibrations become just opposite to each other and neutralize each other; then the slower vibration will again fall more and more behind till it is a whole vibration behind the faster, and the two vibrations will then add and intensify each other. This is what has happened in the experiment with the pendulums. The same thing happens with the electrical vibrations of the condenser circuits that are coupled together.

Theoretical Values of Wave Lengths in the Coupled Circuits. — Let us now return to the experiments with the condenser circuits. By the use of the wave meter we can pick out and measure each of the periods or the corresponding wave lengths of the connected system of condenser circuits. When this has been done, we shall find that the wave lengths obtained satisfy the following theoretical relations [1]:

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[1] Lord Rayleigh, Theory of Sound; J. v. Geitler, Sitz. d. k. Akad. d. Wiss. z. Wien, February and October, 1905; B. Galitzine, Petersb. Ber., May and June, 1895; V. Bjerknes, Ann. der Physik, Vol. 55, p. 120, 1895; Oberbeck, Ann. der

$$\lambda_1' = \sqrt{\frac{\lambda_1^2 + \lambda_2^2 + \sqrt{(\lambda_1^2 - \lambda_2^2)^2 + 4\tau^2\lambda_1^2\lambda_2^2}}{2}}, \qquad (1)$$

$$\lambda_2' = \sqrt{\frac{\lambda_1^2 + \lambda_2^2 - \sqrt{(\lambda_1^2 - \lambda_2^2)^2 + 4\tau^2\lambda_1^2\lambda_2^2}}{2}}. \qquad (2)$$

In these equations

λ_1 = the natural wave length of the primary alone,

λ_2 = the natural wave length of the secondary alone,

τ = the coefficient of coupling, defined by the equation,

$$\tau = \sqrt{\frac{M^2}{L_1 L_2}}, \qquad (3)$$

where

M = mutual inductance between the two circuits,

L_1 = self-inductance of the primary,

L_2 = self-inductance of the secondary, and λ_1' and λ_2' are the resultant wave lengths in both primary and secondary when the circuits are coupled together.

I shall give[1] a few measurements of the wave lengths obtained with the coupled condenser circuits, together with a comparison with values computed from formulas (1) and (2).

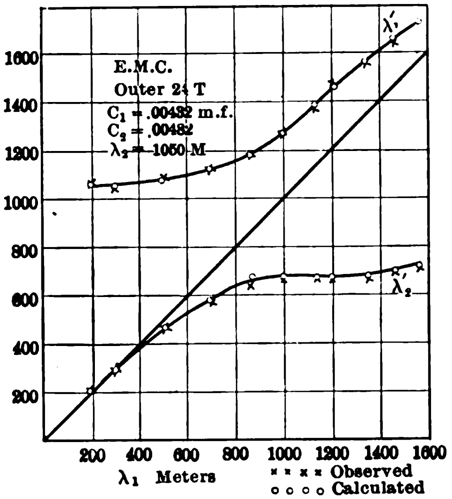

FIG. 160. Curves showing observed and calculated values of the two wave lengths produced by two condenser circuits inductively coupled.

Experiment with Inductively Connected Circuits. L_2 = 24 Turns of Outer Coil. (Fig. 155) λ_2 = 1060 Meters.— The results obtained in this experiment are plotted in Fig. 160, and a complete record of the observations is given in Table XIII.

Physik, Vol. 55, p. 623, 1895; Domalip and Kolacek, Ann. der Physik, Vol. 57, p. 731, 1896; M. Wien, Ann. der Physik, Vol. 61, p. 151, 1897, and Ann. der Physik, Vol. 8, p. 686, 1902; compare also Webster, Theory of Electricity and Magnetism, p. 499, 1897, and Fleming, The Principles of Electric Wave Telegraphy, p. 209, 1906; also Cohen, Bul. Bu. of Standards, Vol. 5, p. 511, 1909.

[1] For a fuller description of these experiments and several others of a similar character see Pierce: Physical Review, Vol. 24, p. 152, 1907.

TABLE XIII

INDUCTIVELY CONNECTED SYSTEM

Primary capacity .00432 microfarad.
Primary inductance varied.
Secondary capacity .00482.
Secondary inductance 24 turns outer coil, $L_2 = 6.60 \times 10^{-5}$ henry.
Wave length of secondary $\lambda_2 = 1060$ meters.

Turns Primary.	L_1 Primary Inductance. Henry.	M Henry.	τ^2
50	15.85×10^{-5}	6.52×10^{-5}	.412
45	13.9	6.14	.421
40	11.8	5.80	.430
35	10.0	5.12	.397
30	8.20	4.45	.360
25	6.50	3.56	.295
20	4.82	2.70	.228
15	3.15	1.95	.183
10	1.72	1.20	.128
5	.69	.47	.048
3	.32	.23	.0277

Turns Primary.	λ_1 Meters.	Calculated.		Observed.	
		λ_1' Meters.	λ_2' Meters.	λ_1' Meters.	λ_2' Meters.
50	1560	1740	727	1750	710
45	1460	1670	712	1650	685
40	1350	1567	686	1570	465
35	1230	1462	680	1480	660
30	1130	1390	660	1370	660
25	1000	1273	685	1280	660
20	870	1185	680	1185	630
15	700	1127	595	1125	565
10	510	1080	467	1090	460
5	300	1060	292	1040	285
3	210	1062	193	1075	210

The method of taking the observations is as follows: First, the condenser C_2 (=.00482 mf.) was connected in series with 24 turns of the outer coil (Fig. 155) and was provided with a spark gap. In this position, with the inner coil thrown out of circuit by disconnecting both plates of its condenser, the wave length λ_2 was found to be 1060 meters. Next, with the secondary condenser disconnected, the wave length of the primary (inner) circuit was determined with its condenser C_1 (=.00432 mf.) connected in series with 50 turns of the inner coil. This wave length λ_1 was 1560 meters. Next, with the primary left unaltered, the secondary was closed by attaching its condensers without spark gap to the 24 turns of the outer coil. This is the case of the closed secondary, and when the discharge was established in the primary, the wave lengths were found to be $\lambda_2' = 710$ meters and λ_1' 1750 meters. The values of λ_2' and λ_1' were plotted against $\lambda_1 = 1560$, Fig. 160. Now decreasing the primary inductance to 45 turns, the values $\lambda_1 = 1460$, $\lambda_1' = 1650$ and $\lambda_2' = 685$ were obtained, and the last two values were plotted against the value of λ_1, and so forth. The complete curves of Fig. 160 were obtained in this way. In the curves of Fig. 160 the *crosses* are the observed values and the *circles* are the corresponding calculated values. The 45° line between the two curves may be looked upon as λ_1 plotted against itself, while a horizontal line across the figure at 1060 meters (not shown) would represent the graph of λ_2. With this in mind it will be seen that the two derived wave lengths λ_1' and λ_2' approach λ_2 and λ_1 respectively toward the origin. The observed and the calculated values are in satisfactory agreement.

The formulas for the calculation of λ_1' and λ_2' are the formulas (1) and (2) of page 236, which involve merely the independent periods of the two circuits and their coefficient of coupling. The latter quantity was obtained by the measurement on a Rayleigh's bridge of L_1, L_2 and M for each setting of the oscillation circuit. The values of these inductances and the values of τ calculated from them is also included in Table I.

The intensity of the various periods of the circuits under the different conditions of the experiment varies greatly. No attempt was made to determine these intensities and the experiments are designed merely to show the wave-length relations.

Experiments with the Inductively Connected System in the Special Case Where $\lambda_2 = \lambda_1$. — A case of especial interest is the case in which the primary and secondary have the same independent periods. This is the case of so-called "resonance" between the two circuits. In this case the wave-length formulas (1) and (2) become greatly simplified, as may be seen by substituting $\lambda_2 = \lambda_1$ in these equations, which under this condition become

$$(\lambda_1')^2 = \lambda_1^2 (1 + \tau), \tag{4}$$

$$(\lambda_2')^2 = \lambda_1^2 (1 - \tau). \tag{5}$$

In the present experiment the two independent wave lengths λ_1 and λ_2 were made equal, and the wave lengths produced by the compound system were then measured and compared with calculations from the formulas (4) and (5). Two wave lengths λ_1' and λ_2' were obtained both by measurement and by calculation. The observed and calculated results are plotted in the curves of Fig. 161. In this case also the agreement is fairly satisfactory.

These two experiments with the inductively connected system of circuits give an experimental verification of the formulas (1), (2), (3), (4) and (5), and serve to show how the wave lengths obtained with the connected system depend on the constants of the two circuits. We shall return to this subject after giving briefly the results of an experiment with the direct coupled system of circuits.

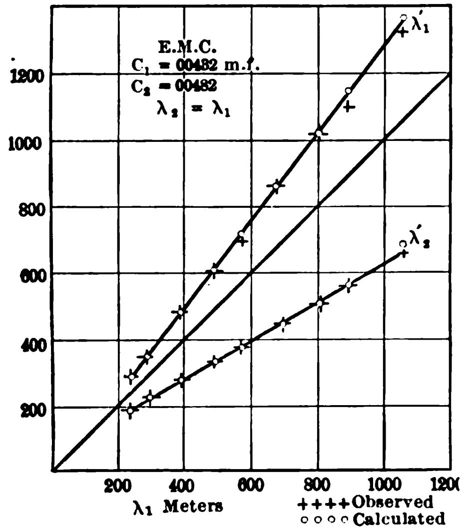

FIG. 161. Curves of wave lengths obtained with inductively coupled condenser circuits having individually the same period.

Experiment with the Direct Coupled Circuit. — **C_2 = .00178 Microfarads, L_2 = 25.5 Turns = 6.7 × 10^{-5} Henrys, λ_2 = 645 Meters.** — The apparatus for this experiment with the direct circuit is shown in Fig. 156. The steps of the experiment are similar to those with the other system of circuits. The observed and calculated values of the wave lengths in the compound oscillating system are plotted in Fig. 162. The formulas of calculation are the formulas (1) and (2), and the agreement between the observed and calculated results (crosses and circles) is seen to be satisfactory.

One interesting result shown by this experiment is the fact that the curve λ_2' comes down to the horizontal axis in the neighborhood of $\lambda_1 = 1010$ meters. This point is the point of so-called *perfect coupling*, and was obtained when the primary and secondary condensers were both connected through the *same inductance*, 25.5 turns of the coil, as shown in Fig. 163.

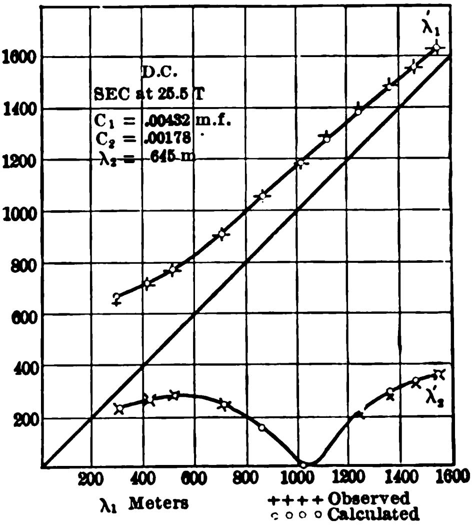

FIG. 162. Curves showing observed and calculated values of the two wave lengths produced by two condenser circuits directly coupled.

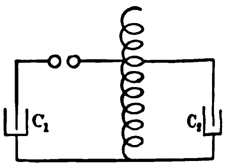

FIG. 163. Diagram of a case of coupling that gives but a single wave length.

In this case we may explain the result in two ways:

(I.) The two condensers may be looked upon as discharging in parallel through the same inductance, and producing, therefore, only one wave of wave length

$$\lambda_1' = 2\pi \cdot v \cdot \sqrt{L_1(C_1 + C_2)} = \sqrt{\lambda_1^2 + \lambda_2^2}. \qquad (6)$$

II. This result is also obtainable from the theoretical equations (1) and (2)

$$\lambda_1' = \sqrt{\frac{\lambda_1^2 + \lambda_2^2 + \sqrt{(\lambda_1^2 - \lambda_2^2)^2 + 4\tau^2\lambda_1^2\lambda_2^2}}{2}}, \qquad (1)$$

$$\lambda_2' = \sqrt{\frac{\lambda_1^2 + \lambda_2^2 - \sqrt{(\lambda_1^2 - \lambda_2^2)^2 + 4\tau^2\lambda_1^2\lambda_2^2}}{2}}. \qquad (2)$$

For when the primary and secondary condensers are connected about the same inductance,

$$L_1 = L_2 = M,$$

therefore

$$\tau^2 = \frac{M^2}{L_1 L_2} = 1.$$

When τ is equal to unity *the coupling is said to be perfect* and the equations (1) and (2) become

$$\lambda_1' = \sqrt{\lambda_1^2 + \lambda_2^2};$$

and

$$\lambda_2' = 0.$$

That is to say, the oscillation, as shown also by method I, becomes single-valued.

The case of perfect coupling was not observed in the experiments with the *inductively coupled system*, because for perfect coupling the primary and secondary coils must have the same number of windings and the two coils must be so close together as to be practically coincident,—conditions that could not be realized with the inductive coupling.

Close Coupling and Loose Coupling. — One of the most interesting facts derivable from an examination of the equations (1) and (2), which are verified by the experiments, is the influence of the coefficient of coupling (τ) on the wave lengths produced by the coupled circuits. In general, two wave lengths are obtained when a coupled system of circuits is set into oscillation. This duplicity of the wave length is often an inconvenience in wireless telegraphy, because, to avoid interference when a neighbor is sending a message we do not wish to hear, it is necessary to tune to avoid, not one undesired wave, but two.

The influence of the coefficient of coupling on the wave length is very easy to investigate in case the primary and secondary of the coupled system are attuned to the same wave length λ, as they generally are in practice. In this case, the formulas for the compound wave lengths λ_1' and λ_2' become the simple forms of equation (4) and (5); namely,

$$(\lambda_1')^2 = \lambda^2 (1 + \tau), \tag{4}$$

and

$$(\lambda_2')^2 = \lambda^2 (1 - \tau). \tag{5}$$

Dividing each of these equations by λ^2, and extracting the square root, we have,

$$\frac{\lambda_1'}{\lambda} = \sqrt{1 + \tau} \tag{7}$$

$$\frac{\lambda_2'}{\lambda} = \sqrt{1 - \tau} \tag{8}$$

Now, putting in various values of $\tau = (.1, .2, .3,$ etc., up to $1.0)$, we obtain the relative values of λ_1' and λ_2', shown in the curves of Fig. 164.

These are all of the possible values of the derived wave lengths λ_1' and λ_2' for the given wave length λ, because τ cannot be greater than unity.

Circuits coupled together with a large value of τ are called *close-coupled circuits;* those coupled with a small value of τ are called *loose-coupled.* The looser the coupling, the nearer the two derived wave lengths approach the wave length of each condenser circuit alone. For sharp resonance, then, the coupling ought to be loose; while for strength of signals the coupling ought not to be too loose.

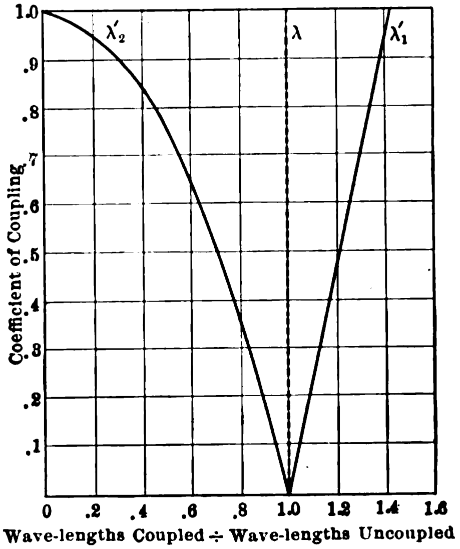

Fig. 164. Effect of coefficient of coupling on the resultant wave lengths of a coupled circuit.

Similar considerations apply more or less directly to the receiving circuits also. This subject, of the closeness or looseness of the coupling, will come up again in connection with the actual wireless telegraph sending and receiving circuits, comprising an antenna circuit coupled with a condenser circuit, which are discussed in the next chapter.

CHAPTER XXII

TUNING THE SENDING STATION

HAVING investigated, in the preceding chapter, the conditions of resonance and the manner of vibration of two condenser circuits connected together, it is proposed now to consider the actual wireless telegraph sending circuits. For this purpose let us examine the method of adjusting the direct coupled or the inductively coupled sending station to resonance. A diagram of a direct coupled sending station is shown in Fig. 165. The condenser *C*, repeatedly and periodically charged from a transformer *Tr*, discharges through a spark gap *G* and a few turns *P* of a "helix." The oscillations in this circuit act inductively and produce oscillations in the antenna circuit consisting of the antenna, the coils *S* of the helix, and the ground *E*. A maximum effect is produced when these two circuits are properly adjusted to each other. A photograph, Fig. 166, is given to show the construction of the sending helix (right) and a method of inclosing the spark gap for reducing the noise of the spark.

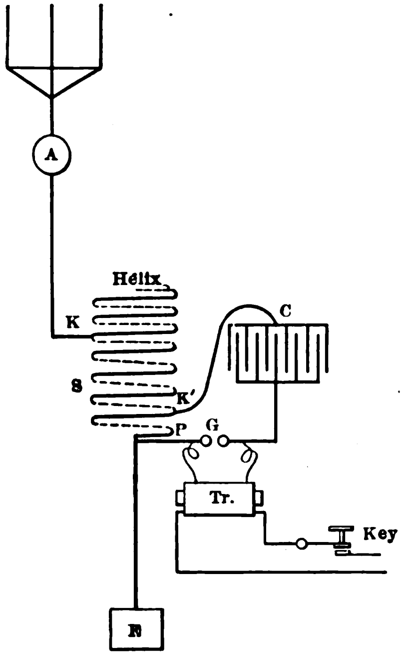

FIG. 165. Direct coupled transmitting station.

A diagram of the inductively coupled sending circuit is shown in Fig. 167. Here the primary and secondary inductances are parts *P* and *S* of two separate helices. These two helices may be one above the other, as represented in the diagram, or may be one

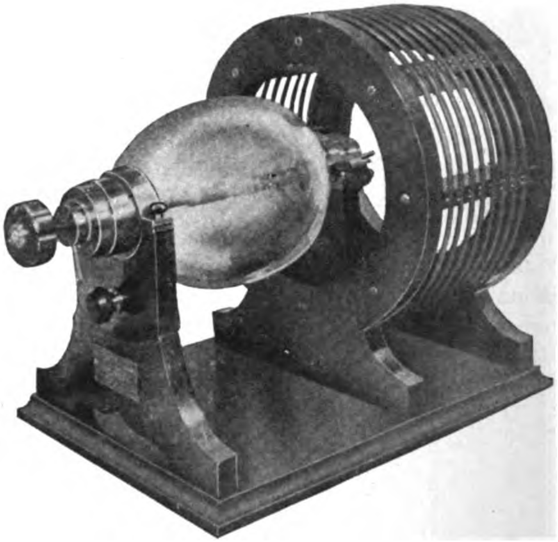

Fig. 166. Showing construction of helix and spark gap for a direct coupled transmitter.

inside of the other, as shown in the photograph of Fig. 168. They must, however, be separated by sufficient distance to prevent sparking between them when the station is in operation. In this system of circuits also, the condenser circuit and the antenna circuit must be adjusted to resonance, in order to get strong oscillations in the antenna.

We shall show the details of the process of attuning the primary and secondary of the coupled circuits to resonance (1) by the use of a wave meter, and (2) by the use of a hot-wire ammeter.

Wave-Metrical Method of Attuning a Direct Coupled Sending Station. — To adjust the station to resonance one first disconnects the condenser circuit, as shown in Fig. 169, and places the wave

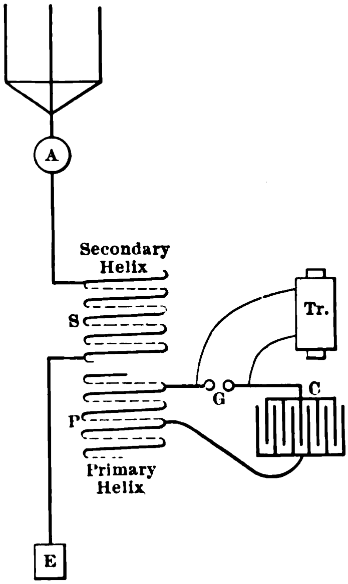

Fig. 167. Inductively coupled transmitting station.

meter *WM* up near the helix. The lower end of this helix is connected through a spark gap to the ground. The secondary of the station's transformer is connected about the spark gap. The antenna is connected by means of a clip contact *K* to some particular number of turns of the helix. The transformer is set into operation so as to produce a spark at the gap.[1] This sets up oscillations in the antenna circuit, and the wave meter is adjusted to resonance with these oscillations. The wave length is read, and this reading

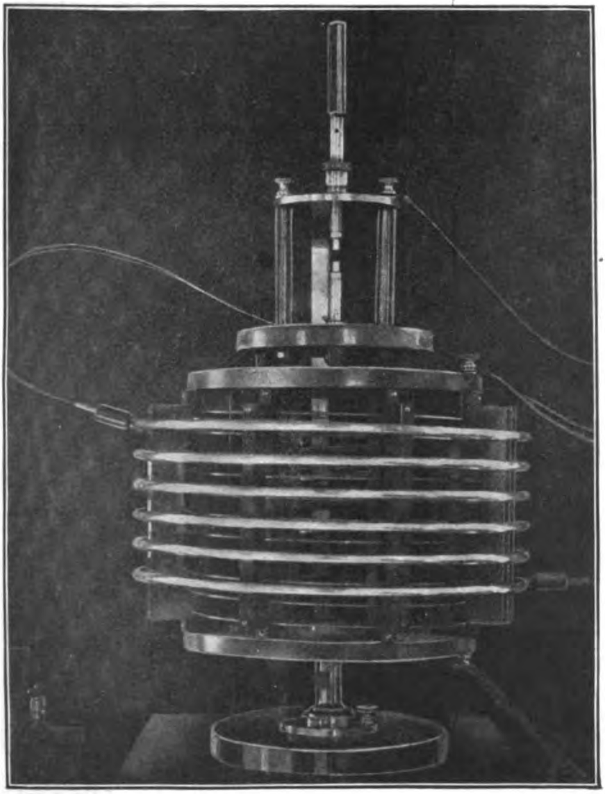

FIG. 168. Showing construction of the helices of an inductively coupled transmitting station.

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[1] In this case, where the spark gap is in the antenna circuit, there is a tendency for the spark to go over into an arc and not produce good oscillations. This may be obviated by playing a small blast of air on the spark.

of wave length, together with the number of turns of helix, is entered in a table. The clip contact is now moved to another point on the helix, thus putting in more or less inductance in the circuit, and the wave length is again determined and entered with the number of turns in the table. A table is thus formed for the wave length corresponding to various numbers of turns of the helix.

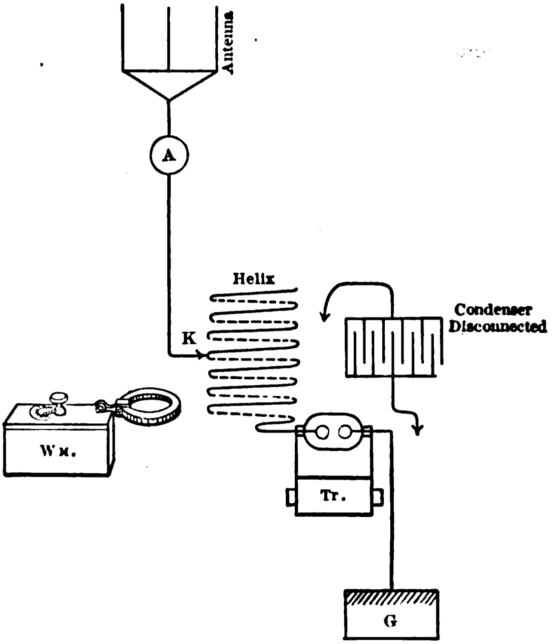

Fig. 169. Method of determining wave length of antenna circuit.

These results are then plotted, and give a curve like that marked " Antenna Circuit " in Fig. 170.

A similar operation is performed with the condenser circuit. In this case the antenna and ground, see Fig. 171, are disconnected; and the condenser circuit, with the spark gap in series, is connected with various numbers of turns of the helix; and the wave length for each case is determined, and a curve of wave lengths against turns is plotted. The curve for this case is put on the same chart with the antenna observations, and marked "Condenser Circuit," Fig. 170. By a reference to the curves we can now obtain the number of turns required either in the condenser circuit or in the antenna circuit to produce

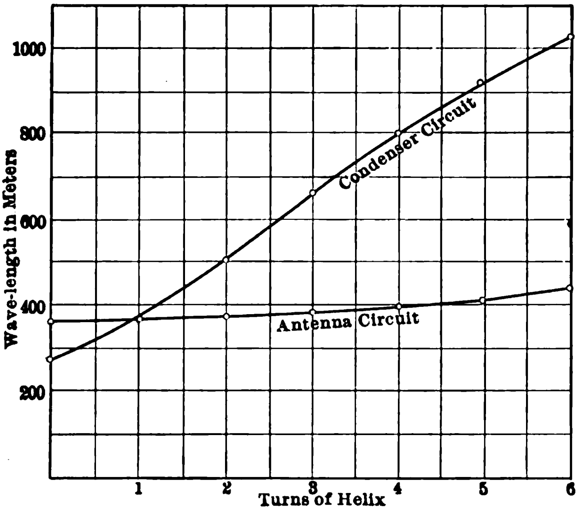

FIG. 170. Curves showing wave lengths of antenna circuit and condenser circuit with different numbers of turns of the helix.

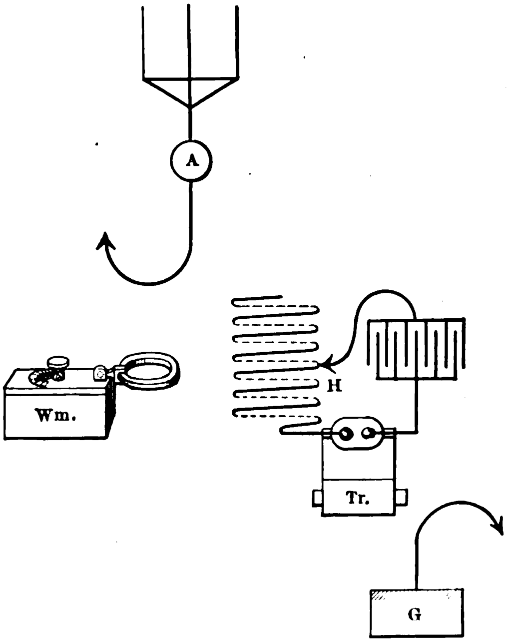

FIG. 171. Method of measuring wave length of the condenser circuit.

a given wave length. For example, let it be required to have both the condenser circuit and the antenna circuit produce a wave length of 420 meters. One sees that to get this wave length in the condenser circuit one must use 1.4 turns of the helix, and to have the same wave length in the antenna circuit when alone, one must use in this circuit 5.1 turns.

Hence, if we connect the condenser about 1.4 turns of the helix, and the antenna and ground about 5.1 turns of the helix, we shall have the two circuits in resonance,[1] and shall get powerful oscillations induced in the antenna circuit under the action of the discharge in the condenser circuit. The method of making the required connections is shown in Fig. 165.

Although the primary and secondary are now connected in resonance, the electrical vibration of the system is not a simple vibration giving 420 meters wave length. If we bring the wave meter up near the coupled system in operation, two positions of resonance are found on the wave meter corresponding to two wave lengths. In the actual case, from which the above numerical values were taken, these two wave lengths obtained were $\lambda_2' = 358$ meters and $\lambda_1' = 462$ meters. This duplicity of resultant wave length exists in the antenna circuit and also in the condenser circuit and therefore gives rise to a series of beats like those obtained with the coupled pendulum experiments, described in the preceding chapter.

FIG. 172. Rotating mirror spark of the double oscillation in the antenna of an inductively coupled transmitting station.

Photograph of the Double Oscillation in the Antenna Circuit. — In a wireless telegraph station attuned to resonance, as just described, I inserted a small spark gap in the lead to ground just below the helix, and took a revolving-mirror photograph, a negative of which is shown in Fig. 172. Although this photograph had to be made with a very brief exposure and is therefore faint, the beats are clearly visible, and at about every fourth oscillation the beats reduce the antenna current to zero.

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[1] Compare Paragraph on "Detuning" on p. 251.

Adjustment of Direct Coupled Sending Station to Resonance with the Aid of a Hot-wire Ammeter. — Another method of adjusting the condenser circuit and the antenna circuit to resonance makes use of a hot-wire ammeter, inserted in the antenna circuit as represented at A, Fig. 165. This instrument contains a fine wire through which the oscillations pass, producing heat. The heated wire expands, and by means of a delicate gearing attachment, the sagging of the expanding wire acts upon a hand passing over a dial. The movement of the hand over the dial is thus an indication of the amount of current passing through the sensitive wire. The instrument may be calibrated directly in amperes, but this calibration (chiefly on account of the shunts that have to be employed) is without much absolute value, when the hot-wire ammeter is used with the very rapid oscillations of wireless telegraphy. Nevertheless, a maximum deflection of the instrument indicates a maximum of current in the antenna, and this is all that is required of the hot-wire ammeter in order to decide when the antenna and condenser circuits are in resonance.

Instead of inserting the hot-wire ammeter in the antenna above the helix, it may just as well be placed in the lead from the helix to the ground. In either case oscillations in the antenna circuit pass through the instrument.

To tune up a station with a hot-wire ammeter, let the station be coupled up as shown in Fig. 165. Set the transformer in action, and read the hot-wire ammeter. Now keeping the spark gap constant, and leaving the antenna clip K unchanged, move the clip K' of the condenser circuit to a different number of turns of the helix, and again read the current. Make a table containing the number of turns of helix in primary circuit and corresponding hot-wire ammeter readings. Then plot a curve of readings against turns in the form shown in Fig. 173. From this figure it is seen that the maximum reading of the ammeter was obtained when the primary was discharging through 1.3 turns of the helix. This is, therefore, the adjustment that must be given to the primary inductance in order to bring the condenser circuit into resonance with the antenna circuit, for the fixed value of the secondary inductance employed throughout the adjustment.

Since the readings of the hot-wire ammeter depend on the values of the mean square current through it, one can, by a process like that described, find out just what conditions of the two circuits give the greatest mean square current in the antenna, and if everything is kept constant in the experiment except the inductance variation, one can determine the resonance adjustment by the maximum reading of the ammeter. But in extending the use of this instrument to other conditions it is necessary to keep in mind that the readings of the ammeter do not give any information of the current amplitude of an individual oscillation; it always gives the average integral effect of a large number of oscillations, and this is not by any means the determining factor in the transmission of messages.

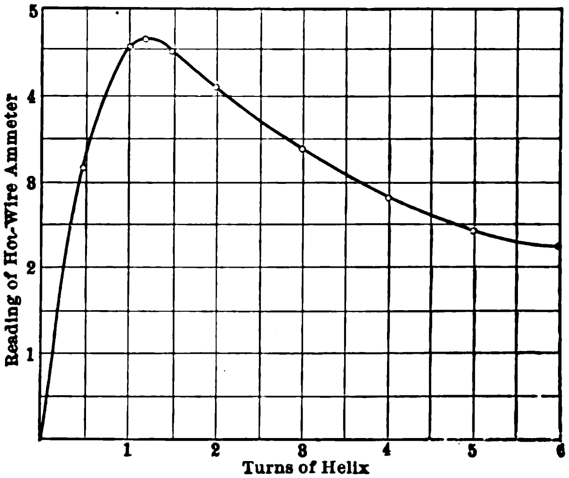

FIG. 173. Hot-wire-ammeter resonance curve of direct coupled sending station.

The wave meter method of attuning the circuits is to be preferred, because it gives the actual wave lengths finally attained, and this is necessary when it is required to set several stations so that they will emit particular predetermined wave lengths.

Tuning the Inductively Coupled Transmitter. — From what has been said in regard to the tuning of the direct coupled transmitter, no difficulty will be encountered in making the small modifications that are necessary to adapt the directions to inductively coupled apparatus. So the discussion will not be repeated.

Coefficient of Coupling. — In some apparatus of the inductively coupled type the distance between the primary helix and the secondary helix can be varied; this varies the mutual inductance of the circuits, and consequently the coefficient of coupling. The diminution of this coefficient by increasing the distance between the primary and secondary helices brings the two resultant wave lengths produced by the station closer together, and gives a sharper wave system than that obtained with a large coefficient of coupling. The coefficient of coupling of the direct coupled system also may be varied, for example, by introducing more or less inductance (not mutual) in one of the circuits.

The question as to the best coefficient of coupling to employ at the transmitting station is difficult to decide. The question is complicated by the conditions that exist at the receiving station as well as at the sending station. I shall therefore defer a consideration of this question until after a discussion of the resonant relations at the receiving station.

The Detuning of Coupled Circuits. — We have shown in the preceding paragraphs how the condenser circuit and the antenna circuit may be adjusted to resonance. This gives in the coupled system a maximum flow of current and a maximum radiation of energy from the antenna. The energy radiated is, however, in the form of two waves of different wave lengths. Suppose this doubly periodic wave to be received by a receiving circuit. Can we not tune the receiving circuit either to the one or to the other of the received wave lengths? And would it not be preferable to adjust the transmitting condenser circuit to a little longer or a little shorter wave than the transmitting antenna circuit in order to strengthen the longer or the shorter wave of the coupled system at the expense of the other wave which is not to be used at the receiving circuit? Professor M. Wien[1] shows that a small advantage (in some cases as great as 30%) may be derived from a process of this kind provided the condenser circuit and the antenna circuit are differently damped. In his experiments Wien used a simple, low-resistance receiving circuit, and I am unable to say how great would be the advantage in a similar *detuning* operation, when the coupled receiving circuits and the high-resistance detectors of actual practice are used at the receiving apparatus. In my own experiments I have never detected any appreciable advantage in detuning an actual sending station.

Possible Existence of Three Wave Lengths in a Coupled System. — With the condenser circuit and the antenna circuit attuned to the same independent wave length, as in the case of our wave metrical illustration on page 248, there is the possibility of the

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[1] Annalen der Physik, Vol. 25, p. 1, 1908.

wave meter giving indications of three wave lengths instead of two. In the case described, two of the wave lengths would be 358 meters and 462 meters, and there would also be a third wave length which would be the wave length of the uncoupled antenna circuit; namely, 420 meters. The reason is this: After a certain number of oscillations the current in the condenser circuit becomes so small that the spark in this circuit extinguishes. This opens the primary circuit, and we no longer have a coupled system; so that the secondary goes on oscillating with its own natural period. This is shown in my spark photograph on page 248. After about four beats shown by the minima in the picture, the beats cease and the secondary circuit goes on oscillating. In the picture it can be seen that up above the point where the beats have ceased the oscillation is a simple oscillation, and these in the original photograph can be followed for more than twenty oscillations. The result is like that which would be obtained with the two coupled pendulums if we should cut loose the primary pendulum at one of its positions of rest, leaving the secondary to vibrate alone.

With the electric circuits this effect of stopping the primary current and allowing the secondary to go on vibrating has been employed with considerable success in the *quenched-spark* method of producing oscillations, which is treated in the next chapter.

CHAPTER XXIII

SOME RECENT METHODS OF EXCITING ELECTRIC WAVES THE SINGING ARC, THE SINGING SPARK, AND THE QUENCHED SPARK

THUS far in this account, practically only one method of producing oscillations at the sending station has been described; namely, the method making use of the spark discharge of a condenser which has been charged from an alternating current transformer or an induction coil. Electric waves produced in this way occur in discrete trains.

Recently several new methods of exciting the oscillations have come into use. We shall begin the discussion of these newer methods by describing the " singing arc," which is a wide departure from the ordinary spark discharge. The singing arc operates on a direct current source, produces a practically continuous sequence of waves, and has met with application, not only to wireless telegraphy, but also to wireless telephony. The history of the singing arc may be traced back more or less connectedly to an early experiment by Elihu Thomson.

Elihu Thomson's Continuous Current Spark. — In 1892 Professor Elihu Thomson[1] found that electric oscillations could be produced from a 500-volt direct current source by connecting the source through a resistance with a spark gap which was shunted by a condenser and inductance. This form of circuit is represented in Fig. 174. A source of direct electromotive force of 500 volts is shown at *E*. This is connected in series with a resistance *R* and a spark gap. In parallel with the gap a condenser *C* and a self-inductance *L* are shunted. Under these conditions electric oscillations were found to be present in the condenser circuit. In the effort to intensify and steady the effects Professor Thomson used a blast of air or a magnet to blow out the spark. This apparatus of Professor Thomson with some modifications and improvements has been reverted to in some of the recent developments of wireless telegraphy and telephony.

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[1] U. S. Patent, No. 500,630, July 4, 1892.

Simon's Talking Arc. — Let us also recall beginnings made in another direction. In 1898, Professor H. Th. Simon,[1] of Göttingen in Germany, found that the vapor path of an ordinary electric arc lamp could be set into mechanical vibration by variation of the current through the arc, and that the vibrating vapor path would communicate its disturbances to the air in the form of sounds. In this way, if a microphone transmitter is employed to vary the current through the arc, as shown in Fig. 175, the arc can be made to reproduce speech with sufficient intensity to be heard throughout a large auditorium. The experiment is very striking and interesting.

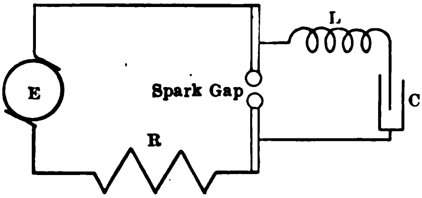

FIG. 174. Diagram of Elihu Thomson's direct current spark.

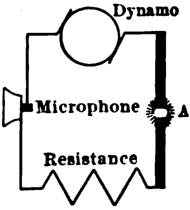

FIG. 175. Professor Simon's talking arc.

Duddell's Singing Arc. — In 1900 Duddell[2] published an account of some similar experiments with the arc, in which the arc was made to produce electric oscillations and to give out a musical note. This was brought about by shunting the arc with a condenser and inductance, in a manner resembling that employed by Elihu Thomson. The Duddell circuit is shown in Fig. 176, and differs from the corresponding circuit of Elihu Thomson by the substitution of an arc between carbon electrodes for the metallic arc or spark of Thomson. In Duddell's apparatus (Fig. 176) the arc *A*, consisting of two solid carbon electrodes, is connected in series with a direct-current generator *E*, a resistance *R* and a self-inductance *L*. About the arc are shunted a condenser *C* and

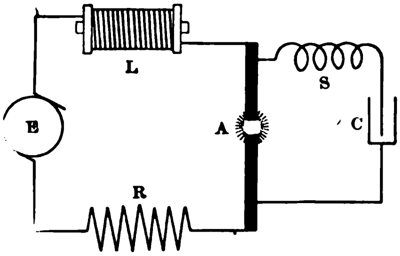

FIG. 176. Duddell's singing arc.

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[1] Wied. Ann., Vol. 64, p. 233, 1898; Physikalische Zeitschrift, Vol. 2, p. 253, 1901.

[2] Journ. Inst. of Elec. Eng., Vol. 30, p. 232, 1900.

an inductance S. With proper adjustments of the various parts of the circuit the arc emits a musical sound which in Duddell's experiments could be plainly heard to a distance of several meters. The pitch of the note can be varied by varying the capacity C or the inductance S. The experiment is highly interesting when one varies the capacity C by means of a set of keys and thereby produces a succession of notes of different pitches.

In addition to the evidence afforded by the emission of musical sounds, the shunt circuit comprising the condenser C, the inductance L and the arc A, may be shown also by its inductive action on a neighboring circuit to be traversed by a pulsating or oscillating current. We have thus a pulsating or oscillating current produced from a direct-current source.

Why the Arc Gives Rise to Pulsating Currents. — The explanation of the production of oscillatory currents and audible sounds by the arc shunted with a condenser has been the subject of a considerable amount of theoretical and experimental investigation.[1] Duddell's original account of the phenomenon contains a simple explanation, which is substantially as follows:

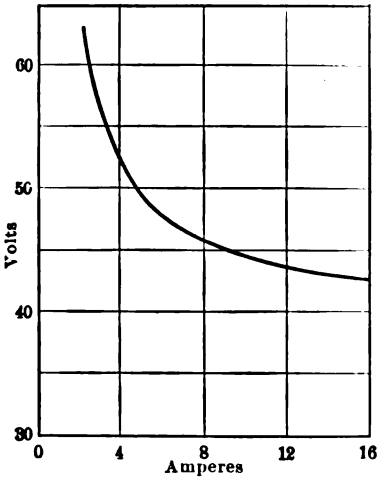

FIG. 177. Volt-ampere characteristic of carbon arc.

The electric arc between carbon terminals has a falling volt-ampere characteristic like that shown in Fig. 177. With an increase of current through the arc the voltage between the arc terminals decreases. For this reason, when the arc is connected in series with a source of voltage and is "struck" by bringing the terminals together and then separating them, the current through the arc tends to increase to a very large value, and must be restrained by a suitable resistance R in circuit with the arc (see Fig. 176).

Suppose, now, that when the arc is quietly burning, a condenser C and inductance S are together connected about the arc. The

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[1] For a theoretical treatment of this subject the mathematical reader is referred to an article by H. Th. Simon, Physikalische Zeitschrift, Vol. 7, p. 433, 1906.

condenser begins to charge. This takes current from the arc and in consequence the voltage between the arc terminals increases; this causes more current to flow into the condenser. Finally, the condenser is charged to the same voltage as that between the terminals of the arc, but on account of the inductance in series with the condenser the current into the condenser continues for a time after this condition is reached. This results in a potential difference at the condenser higher than that at the arc, which finally results in a cessation of the current into the condenser. The condenser then begins to discharge through the arc, causing a drop in the arc voltage and a further discharge of the condenser. While the condenser is discharging, the inductance in series with the condenser tends to preserve the discharging current, so that the condenser potential falls below that of the arc. After the discharge has gone on to a sufficient extent, a minimum of condenser potential is reached, and the process again reverses.

The arc and the condenser circuit are thus in an unstable condition and the condenser continues to charge and discharge, thus repeatedly impoverishing and replenishing the arc as to current. Whatever energy is expended in this oscillation circuit is drawn from the direct-current source.

The fluctuating current through the arc, which is a path of conducting vapor, causes the vapor path to contract and expand periodically, and thus gives a continuous train of periodic disturbances to the air, which are heard as a musical note provided their period of vibration is within the range of audibility.

It is, however, not the musical note, but the oscillating current in the condenser circuit, that is of interest in connection with wireless telegraphy and telephony. For the purposes of wireless telegraphy and telephony it is important that the frequency of oscillation should be high; namely, between one hundred thousand and one million per second. With the ordinary Duddell arrangement of a carbon arc in air this high frequency of oscillation does not seem to be easily obtainable, at least not with a large amount of energy in the oscillating circuit.

Poulsen's Improvement of the Arc Method of Producing Oscillations. — In 1903 Valdemar Poulsen[1] of Copenhagen made an important improvement in the arc method of producing high-frequency oscillations. This improvement by Poulsen consisted

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[1] British Patent, No. 15, 599, July 14, 1903. See also Science Abstracts, Vol. 8, p. 521, Abstract No. 1620, 1905.

primarily in placing the arc in an atmosphere of *coal gas or hydrogen*, and in employing for the arc one terminal of carbon (−) and the other terminal of a water-cooled cylinder of copper (+) (cf. Fig. 178). For the purpose of effecting the cooling of the copper electrode, it was made hollow, and through it a stream of water was circulated. Water was also circulated through a worm within the jacket inclosing the coal gas or hydrogen about the arc, so as to prevent undue heating of this jacket. To enhance the strength and the frequency of the oscillations, the poles of a powerful electromagnet NS are inserted, gas-tight, into the chamber, and placed so as to give a magnetic field transverse to the arc. The carbon terminal of the arc is slowly rotated by a clockwork or electric motor. This is to prevent the formation by the arc of inequalities in the surface of the carbon electrode. When all of these precautions indicated by Poulsen are taken, the oscillations may be given a frequency as high as a million or more per second,[1] which brings them well within the range useful for wireless telegraphy and telephony.

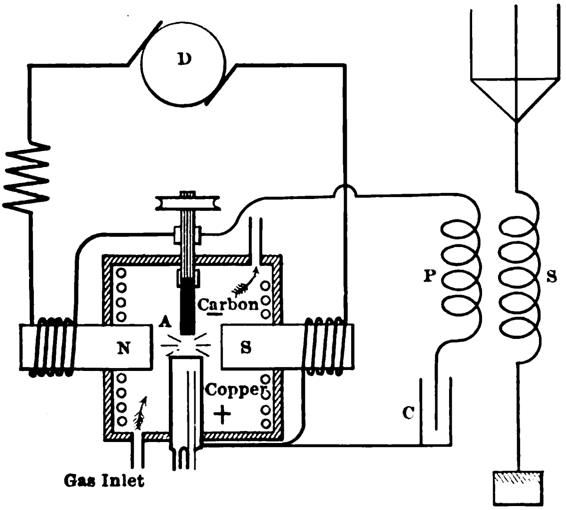

FIG. 178. Mr. Poulsen's singing-arc generator of electric waves.

The source of current is a direct current generator D, giving

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[1] By the use of an arc having a water-cooled copper cathode and a silver-point anode, N. Stschodro (Ann. d. Phys. Vol. 27, p. 225, 1908), has obtained more than 300,000,000 oscillations per second, and has performed Hertz's mirror experiment with the electric waves so produced.

about 500 volts. Leads from the generator pass in series through the arc and around the electromagnet *NS*. About the arc is shunted the condenser *C* and the inductance *P*. The high-frequency oscillation takes place in the circuit *ACP*, and these oscillations are impressed upon the antenna by means of the oscillation transformer *PS*.

Comparison of Arc in Coal Gas or Hydrogen with Arc in Air. — A characteristic difference between the electric arc in an atmosphere of coal gas or hydrogen and an arc of equal length in air is shown in the volt-ampere curves of Fig. 179, taken from an investigation by Mr. W. L. Upson.[1] It is seen that the arc in hydrogen shows a greater fall of voltage with a given increase of current than does the arc in air. For this reason a more energetic oscillation of high frequency can be obtained from the arc in hydrogen than from the arc in air, as may be seen from the following reasoning:

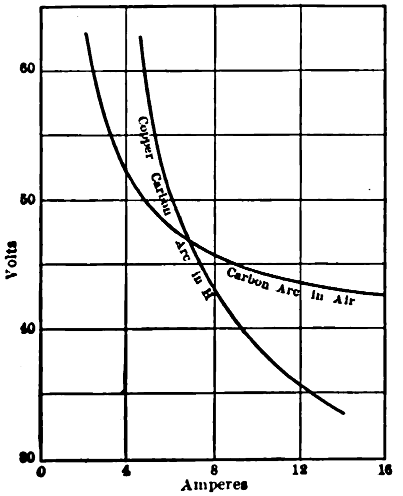

FIG. 179. Volt-ampere characteristic of carbon arc in air and copper-carbon arc in hydrogen (Mr. Upson).

To obtain the high-frequency oscillation a condenser of small capacity must be used in the shunt circuit; whereas for a slow frequency of oscillation a large capacity may be used. Now a small condenser, as is required for the high frequency, takes only a small amount of current to charge it, and for this charge to be energetic it is essential that it should rise to a high voltage. It is therefore essential that the shunting of a small amount of current from the arc should cause a large rise of potential at the arc in order to get energetic oscillations in the shunt circuit. From the volt-ampere curve of hydrogen this is seen to be what happens in case the arc is in an atmosphere of hydrogen. In order to get equivalent steepness of the volt-ampere curve in air, it is seen to be necessary to work with very small currents in the arc; whence it follows that with a small current through the arc, oscillations of high

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[1] Phil. Mag., July, 1907.

frequency can be obtained, even with the arc in air. The surrounding of the arc with an atmosphere of hydrogen permits these high-frequency oscillations to be obtained also with a large current (10 to 12 amperes) through the arc, which is a valuable asset for the sustenance of energetic oscillations.

Instead of employing an atmosphere of hydrogen about the arc, ordinary coal gas, such as is used in illumination, produces also very good results.

One method of feeding the gas into the chamber is to lead it in continuously by a rubber tube connected with the gas jet of the illuminating system. The gas, after passing through the chamber about the arc, is conducted away by a rubber tube leading to the outside of the building, or else it is led to a gas burner and ignited to prevent it from escaping unconsumed into the room.

The Use of Other Hydrocarbon Gases and the Use of Steam About the Arc. — Instead of coal gas or hydrogen, almost any other gaseous hydrocarbon may also be employed with the arc to enhance the energy and improve the constancy of the high-frequency oscillations. For example, the combustion products of an alcohol flame will produce effects in a degree similar to effects with the coal gas. These combustion products may be supplied to the arc by means of a small alcohol lamp placed beneath the arc, as is shown in Fig. 180.

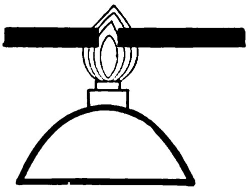

Fig. 180. Carbon arc in alcohol flame.

Similar beneficial effects upon the oscillations are produced by the gases formed by the volatilization of a liquid hydrocarbon, such as turpentine, pentane, amyl alcohol, etc. In this case the liquid hydrocarbon is allowed to fall drop by drop into a cup-shaped depression in one electrode, where it is volatilized and surrounds the arc with an atmosphere of gas.

Dr. Lee DeForest[1] has suggested steam as an atmosphere for the arc, and has shown several methods of supplying steam to the arc. One of these methods is depicted in Fig. 181 taken from DeForest's United States patent specifications.

Use of Several Arcs in Series. — To obviate the necessity of the magnetic field and the coal-gas atmosphere, as used with the Poulsen arc, the Telefunken Company of Germany employs several arcs in series, thus obtaining a high effective voltage. Only a

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[1] U. S. Patent, No. 850,917, issued April 23, 1907.

small current is sent through the arcs. The use of a small current through the arcs, as has been pointed out above, utilizes the steep part of the volt-ampere curve of Fig. 179, so as to obtain large fluctuations of current even *with the arc in air*. The arcs of the Telefunken apparatus have carbon cathodes and water-cooled copper anodes, arranged as in Fig. 182, which shows six of these arcs in series. The tubes T, T, . . . are of copper, and are filled with water for cooling. The bottom of each of the tubes, which are the positive electrodes of the arcs, is recessed and in this recess the arc is maintained. Provisions are made for striking all of the arcs at once, and for separately adjusting their arc lengths. The arcs have a combined terminal voltage of 220 volts and require about 5 amperes. An oscillation circuit comprising the condenser C and the inductance P is shunted about the arcs. The oscillations are communicated to the antenna by means of the oscillation transformer PS.

On the Period of Oscillations Produced by the Duddell and Poulsen Arcs. — The period of the oscillations of the condenser circuit shunted about the Duddell, Poulsen or Telefunken arc is not determined completely by the value of the capacity and the inductance in the oscillating circuit, but is a function also of the length of the arc, the current through it, the material of the terminals, and the nature and pressure of the surrounding gas. Mr. G. W. Nasmyth,[1] by a quasi-theoretical discussion of the problem, has derived the following expression for the time of one complete oscillation:

$$T = \frac{2\pi}{\sqrt{\frac{1}{LC} - \frac{\left(R - \frac{c + ld}{A}\right)^2}{4L^2}}}$$

in which L, C, and R are the self-inductance, capacity and ohmic resistance of the oscillating circuit; l is the length of the arc, A the current through the arc, and c and d are constants depending on the nature of the terminals of the arc and the gas surrounding it.

Mr. Nasmyth finds experimental confirmation of this formula for a large range of frequencies.

On the Continuity of the Oscillations Produced by the Arc. — Instead of being broken up into separate discrete trains, as are the electric waves produced by the spark discharge of a condenser,

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[1] Physical Review, Vol. 27, p. 117, 1908.

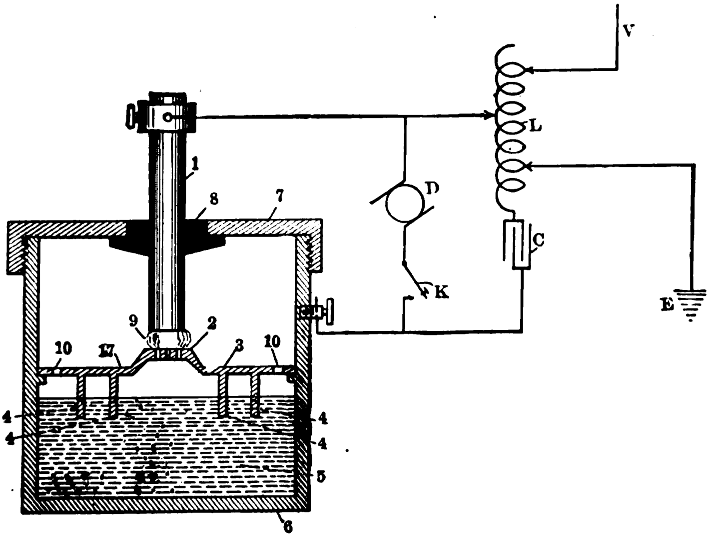

Fig. 181. DeForest's arc in steam.

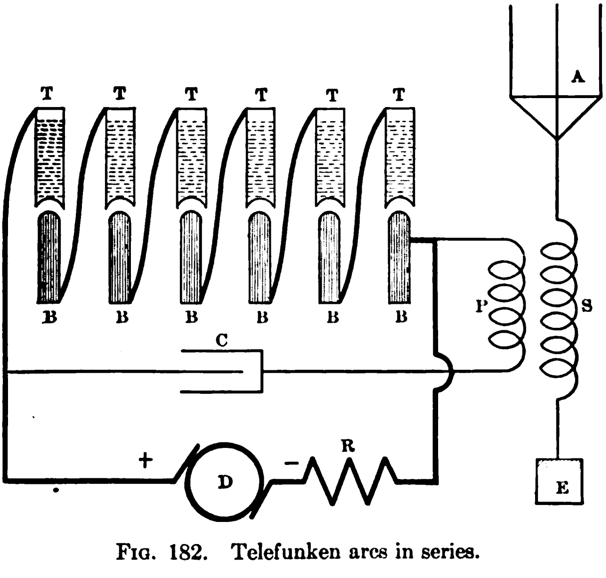

Fig. 182. Telefunken arcs in series.

the waves emitted from a circuit connected with a fluctuating arc follow one another in a continuous sequence. Such a sequence is called a " persistent train of waves." The waves are sometimes called " undamped." This is true in the sense that all the waves have equal amplitude. It is, however, not true in the sense that each oscillation is exactly sinusoidal in form. Under favorable conditions, however, the current may be very nearly sinusoidal, as has been shown by oscillograms taken by Professor Simon.[1]

Use of Persistent Oscillations in Wireless Telegraphy. — Although the individual impulses of a persistent train of waves are not by any means so intense as the maxima obtained with the spark-discharge method of excitation, yet these impulses, arriving continuously at the receiving station, may produce an integral effect that compares with that produced by the waves originating at a station actuated by the spark discharge. Up to the present this result does not seem to have been achieved, so that up to the present time the greatest distances of telegraphic transmission have not been attained with the singing-arc excitation.

For telegraphic signaling, it is evident that the telephone receiver cannot be employed to respond to an unmodified continuously arriving train of waves, because the frequency of these waves is beyond the limit of audibility and beyond the range of the telephone receiver. In order to make these signals audible in the telephone receiver, used with the detector at the receiving station, the train of waves emitted by the sending station must be modified so as to give them a train frequency of audible pitch. This is done by inserting an interrupter, or " chopper," in the oscillating circuit or in the sending antenna circuit. The interrupter breaks up the persistent series of oscillations into discontinuous groups separated by dormant periods, and these groups, arriving one after the other at the receiving station, will, after being suitably rectified by the detector, give the required periodic current in the telephone receiver.

Instead of actually interrupting the oscillating circuit or the antenna, the interrupter may be used to throw an inductance in or out at the sending station and thereby periodically change the resonance relations at the sending station. Such a throwing of the circuits in or out of resonance would produce a periodic strengthening and weakening of the effects received, which would therefore be audible.

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[1] Physikalische Zeitschrift, Vol. 7, p. 433, 1906.

Instead of having the interrupter or detuning vibrator at the sending station, it may be used at the receiving station, as has been proposed by Poulsen.[1] A diagram of a circuit in which this is done, taken from Mr. Poulsen's United States patent specification, is shown in Fig. 183. The receiving antenna circuit *a* is inductively connected with the condenser circuit *b*, *c*, *d*. In shunt about the condenser *d* is a detector *s* with its accessories. A vibrating interrupter at *f* is adapted to connect another condenser *k* periodically in parallel with the condenser *c*. When the contact is interrupted at *f*, assuming that the oscillation circuit is tuned to resonance under these circumstances, intense oscillations will appear in this circuit, and by means of the detector at *s*, which rectifies the oscillations, an integral current will pass through the telephone. If now the contact at *f* is closed, the circuit is thrown out of resonance, oscillations in the circuit *b*, *c*, *d* cease, and the current in the telephone ceases. When the contact at *f* is again opened, another integral current passes through the telephone, which in this way is made to respond with a sound of pitch determined by the frequency of the interrupter.[2]

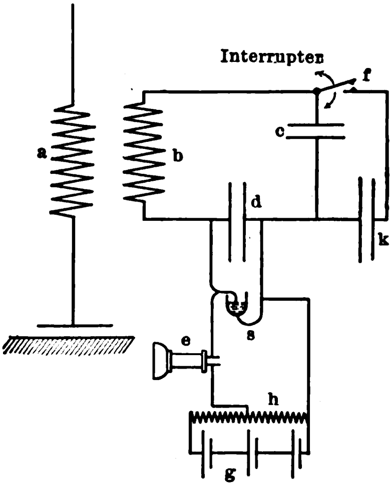

FIG. 183. Receiving circuit for persistent waves (Poulsen).

In order to obviate the necessity of these interrupter devices at the sending or receiving circuit, an Einthoven galvanometer at the receiving station may be used instead of the receiving telephone. Einthoven's instrument will respond to the uninterrupted train of waves and possesses a sensitiveness even greater than the telephone receiver. The deflections of this galvanometer may be photographically recorded. Although this instrument, with the necessary moving film for taking the photographic record of the message, is not quite so simple to install or to operate as the circuit

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[1] U. S. Patent, No. 897, 779, applied for March 6, 1907, issued Sept. 1, 1908.

[2] The explanation given by Mr. Poulsen in his patent specification is inconsistent with the explanation here given.

with telephone receiver, it is, however, sometimes an advantage to have a photographed record of the dots and dashes, rather than to depend upon a correct reading of the message by ear.

The advantage of a written record in the case of wireless telegraphy is perhaps not so great as in the case of the land-line messages, where the operator may be dispensed with at small stations for a good part of the day and the recording apparatus be depended upon completely. This cannot at present be done so well with the wireless messages, especially in the case of transmission of messages to ships at sea, because it is important to have the receipt of the message acknowledged as soon as it is finished; for otherwise, on account of the uncertainty of the position of the ship to which the message is sent and the uncertainty as to whether the message has been received unless acknowledged, considerable misgiving might arise in the mind of the sender of the message. The receiving operator cannot, therefore, well be dispensed with. The presence of the receiving operator is also constantly required in order to effect the tuning of the apparatus so as to adjust it to the different wave lengths employed by different sending stations, and to eliminate signals of undesired wave lengths. Although the recording apparatus at the receiving station is now used to some extent, the detector and telephone receiver are the main dependence for translating the electric waves into intelligible signals.

This, however, is a digression from the subject under consideration, which is the persistent train of waves produced by the singing-arc method of excitation at the sending station.

Advantages of the Singing-Arc Excitation. — The singing-arc method of excitation has the advantage for wireless telegraphy that it permits sharper tuning at the receiving station, and consequently better discrimination between signals of different wave lengths. This advantage arises chiefly from the fact that the persistent train of oscillations gives opportunity for the current at the receiving station to build up to what is called a steady state, and on this account the high resistance of the receiving detectors produces a less deleterious effect on the sharpness of tuning. However, the effect of the high resistance of the detector cannot be completely eliminated, and the gain in sharpness of resonance due to having a persistent train of oscillations does not completely remove the difficulties that arise from interference. Some numerical calculations described near the end of Chapter XXIV and made on the assumption that the incoming waves are undamped, show that the interference difficulties, even with undamped waves, are still considerable.

The main advantage in the singing-arc method of excitation arises in the applicability to *wireless telephony* of this method of producing electric oscillations. Wireless telephony is briefly considered in a subsequent chapter.

As a continuation of the discussion of novel methods of producing oscillations, we shall next describe the Lepel arc and the quenched spark.

The Lepel Arc. — In a German Patent, No. 24,757, filed Aug. 20, 1907, Baron von Lepel has described a very simple and efficient form of discharge gap which is capable of operating on either a direct or an alternating-current source. It consists simply of two circular discs of copper with a thin sheet of paper between them. The discharge occurs between the discs and through the paper. A small perforation made near the center of the paper affords a suitable starting place for the discharge. As the discharge continues, the paper is gradually burned away from the center outwards. This burning away takes place in an atmosphere deficient in oxygen, and consequently requires several hours to use up all the paper. A circular groove cut near the outside edge of the adjacent faces of the copper plates prevents the arc from getting to the outer edge of the discs and there being exposed to the air. The essential feature of the Lepel gap is that the spark or arc shall be very short and shall occur in the space which is deficient in oxygen. The presence of the products of combustion of the paper enhances the efficiency of the arc. The arc will operate on a direct current source, and gives discrete trains of oscillations of which the pitch may be made very high and may be regulated by regulating the condenser about the gap and the rheostat placed in the leads to the current supply.

The series of discharges obtained from the direct-current supply occurs in a manner resembling the occurrence of the series of discharges obtained by Elihu Thomson with his singing spark, as described on page 253. In addition each discharge is rapidly quenched and gives the quenched-spark effect described under the next heading.

The discs of the Lepel arc are 3 to 5 inches in diameter, and, for rapid conduction away of the heat generated, are made of copper or silver, which have high conductivity for heat. The discs may also be made hollow, and are then cooled by the admission of circulating water. The space between the two discs is about .01 inch. The arc operates on 300 to 500 volts direct and employs a current of from 1 to 2 amperes. The inventor[1] claims to have transmitted messages to a distance of 300 miles with less than ½ kilowatt of power. On account of the low voltages employed, the sending condenser is made of mica or paraffined paper and occupies a space of only 4 cubic inches. The apparatus is thus seen to be very efficient and easily portable. Baron Lepel's discharger combines the principle of the singing arc with that of the quenched spark.

The Quenched Spark. — In discussing this subject, let us recall the facts established in Chapters XXI and XXII that a system of two circuits inductively or directly coupled together possesses two separate and distinct wave lengths, even when the two circuits are individually attuned to the same period before coupling together. The existence of this double periodicity in the oscillation of the coupled system is a distinct disadvantage, both because of the difficulty of establishing sharp resonance with such a doubly periodic wave, and also because of its wastefulness of transmitting energy.

A remedy for this defect, as was first pointed out by Professor Max Wien,[2] consists in the use in the primary circuit of a spark that quenches itself out after it has made a few oscillations. This opens the primary circuit so that it is no longer a circuit in active relation to the secondary, and allows the secondary (i.e., the antenna circuit) to go on oscillating with its free natural period. As an illustration of the manner in which this works let us recall our sympathetic pendulum experiment of Fig. 159. It will be remembered that the secondary pendulum is undergoing a maximum of displacement when the primary is at rest. Now, if the primary pendulum is disconnected or stopped while it is at its point of rest, the secondary, which is describing its maximum excursion, will go on vibrating with its large amplitude, and will not have to expend a part of its energy in setting up vibrations again in the primary. The secondary will, therefore, decrease in amplitude only because of its own damping. This is represented in the curves of Fig. 184, which also represent the action in the

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[1] For further discussion of Lepel's invention, together with the inventor's claim of priority against Count Arco, see London Electrician, Vol. 63, pp. 142, 174, 374, 1909.

[2] Physikalische Zeitschrift, Vol. 7, p. 871, 1906.

corresponding electrical case. *P* and *S* represent the current in the primary and secondary oscillating circuit having in the primary an ordinary spark gap. *P′* and *S′* represent the current in the primary and secondary of a system having a quenched spark in the primary. The spark is quenched when the energy in the primary attains its first minimum. If this spark does not recover its conductivity again, the secondary oscillation continues with its own free period and damping as represented in *S′*.

Now it has been shown that a very short spark kept well cooled has exactly this characteristic of rapidly extinguishing after a few oscillations, as is represented by the curve *P′*. A method of attaining a similar result with a comparatively large amount of power consists in using several gaps of the Lepel type in series.

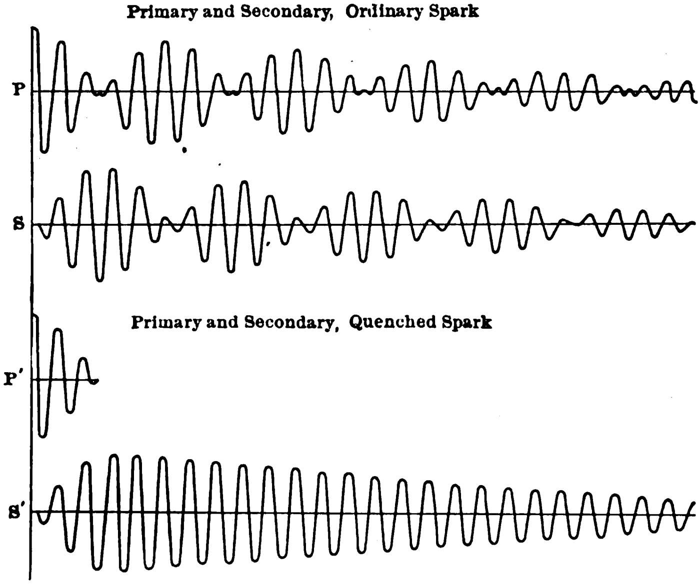

FIG. 184. Curves showing oscillations with ordinary spark and with quenched spark.

This has been done by the Telefunken Company in Germany with marked success. A diagram of the quenched spark, comprised of several minute gaps in series between metal discs, is shown in Fig. 185. The face of one of these discs, which are of copper, is shown in the upper part of the figure. The lower part of the figure shows a section of a pile of these discs, placed so as to give several of the gaps in series. Between each pair of the discs is a thin mica ring with a width extending from the center of the protecting grooves out beyond the face of the disc. The distance between two adjacent discs is about .01 inch, and the diameter of the discs is about 5 inches. The discharge is sent through all of the gaps in series. The result is a quenched spark that will operate on a high voltage, which may be either from a direct current or an alternating current source. With this apparatus the Telefunken Company claim to have transmitted signals to enormous distances with a very small consumption of energy.[1]

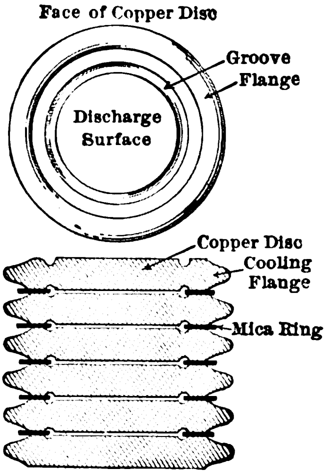

Fig. 185. Quenched-spark discharger.

Peukert's Rotating Quenched Spark in Oil. — Professor W. Peukert,[2] of Brunswick in Germany, has devised a very efficient and regular quenched spark in oil between two parallel discs $\frac{1}{250}$inch apart. One of the discs is stationary, while the other is rotated with a speed of 800 revolutions per minute. For the purpose of keeping the discs at a constant distance apart the moving disc is carried on an axis mounted in conical bearings. For regulating the distance between the plates the stationary plate is adjustable axially. Oil is fed into the narrow crevasse between the plates by a tube passing through the fixed plate. The rotation of one of the plates throws the oil out centrifugally and thus keeps a constant supply of fresh oil in the gap. The Peukert gap operates with a direct current source. The most favorable voltage of the source is between 600 and 700 volts, but 400 or 500 volts will also give good results. The plates which constitute the electrodes should be of pure copper or of copper silvered on the active

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[1] For further information in regard to the quenched spark of this type, the reader is referred to Fleming: Electrician, Vol. 63, June 11, 1909. Telefunken Co.: German Patents, No. 27,164, filed June 23, 1908; No. 27,483, filed Aug. 20, 1908; No. 28,198, filed May 16, 1908. Also various letters and addresses by Count Arco in London Electrician, Vol. 63, 1909.

[2] A report of experiments on the Peukert gap by Dr. A. Wasmus of the Brunswick Technische Hochschule is contained in London Electrician, Vol. 64, p. 550, 1910. The apparatus is to be placed on the market by the Polyfrequenz Electricitäts Gesellschaft.

surfaces. One gap will carry efficiently not more than 4 amperes. The oscillations occur in a practically continuous train and are suitable for wireless telephony. To give a tone to the discharge, so as to adapt it to wireless telegraphy with a rectifier and telephone as receiver, one of the discs may be segmented.

Some Facts in Regard to the Quenched Spark. — Recurring to the curves of Fig. 184, it will be seen wherein consists the advantage of a properly quenched spark; namely, the spark is active only long enough to allow the oscillations of the antenna circuit to build up to a maximum of intensity. The number of oscillations of the primary requisite to attain this is the fewer the closer the coupling between primary and secondary. The intensity of the secondary is a maximum when the current of the primary is a minimum. If the spark completely loses its conductivity at this point, the subsequent oscillations of the secondary induce an electromotive force in the primary, but if no current is established in the primary, no energy is thereby consumed, and all of the energy, which is now stored in the secondary circuit, will stay there until radiated.

If, on the other hand, the primary spark does not completely lose its conductivity at its minimum, the e.m.f. impressed back on the primary by the oscillations in the secondary will reëstablish current in the primary. This current in the primary, flowing as it does repeatedly across the spark gap, heats it, and dissipates a considerable part of the energy of the system as heat in the gap. This recommunication of energy to the primary is worse than useless because in addition to dissipating energy, it is active also in burning away the spark gap and in severely straining and heating the transmitting condensers.

In addition to this loss of energy and the destructive strain on the apparatus, the double periodicity of the vibration, with the use of the unquenched spark, is a hindrance to discriminating tuning of the receiving station.

The quenched spark is, therefore, economical in transmitting energy, and is favorable to sharp tuning; and, by obviating a useless dissipation of energy in the primary circuit, it also materially contributes to the life of the transmitting apparatus.

What are the characteristics of a spark gap in order that it should give a quenched spark ? . After the energy has left the primary circuit, the gap should very rapidly recover its high resistance, so that oscillations will not again be set up in the primary by the reaction of the secondary. This the author found to be the principal characteristic of the Hewitt mercury interrupter,[1] and in the light of the recent investigations of Professor Wien and others on the quenched spark, it is apparent that the high efficiency of the mercury interrupter in exciting oscillations is undoubtedly due to its action as a quenched spark. Unfortunately Mr. Hewitt's mercury interrupter deteriorates and breaks too easily to be serviceable in its ordinary form as a quenched spark. It is possible that a manner of constructing this apparatus may be discovered that will remove its deficiency of short life.

Another very evident quenched spark that has long been in use in America is the gap devised by Mr. Kinraidy for operating his Tesla coil for therapeutic use. Mr. Kinraidy's gap consisted of two water-cooled flat terminals very close together between which the discharge occurred. With this kind of a gap the Kinraidy coil gives extraordinarily long and intense Tesla discharges with the expenditure of only 100 watts in the primary.

The Lepel arc, the Telefunken series of Lepel arcs, the Peukert gap in oil between a fixed and a rotating disc, are very efficient practical forms of quenched spark, and all possess in common the characteristic of a very short spark gap provided with means of rapid cooling so as to effect a speedy restoration of the high resistance of the gap after the energy has left the primary circuit. The credit for foreseeing the importance of this requirement and of indicating means for attaining it belongs to Professor Max Wien.

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[1] G. W. Pierce: Proc. American Academy of Arts and Sciences, Vol. 39, No. 18, February, 1904.

CHAPTER XXIV

RESONANCE OF RECEIVING CIRCUITS. THE POSSIBILITY OF PREVENTING INTERFERENCE

How does the current induced in a receiving antenna depend upon the height of the receiving antenna? How much is the strength of this current modified by tuning the antenna ? In a coupled receiving circuit what resonant relations exist between the two parts of the coupled system ? How sharp is the tuning at the receiving station, and to what extent can interference be prevented ?

It is proposed in this chapter to present a brief examination of these questions.[1] For this purpose some experiments are described.

DEPENDENCE OF RECEIVED CURRENT ON HEIGHT OF RECEIVING ANTENNA

In an investigation to ascertain the dependence of received current on the height of receiving antenna, a direct coupled transmitter, like that illustrated in Figs. 152 and 165 was used to produce the electric waves. The two circuits of the transmitting station were adjusted to resonance with each other by the hot-wire ammeter method of Chapter XXII. The dimensions of the transmitting circuits were as follows: The secondary part *S* of the helix consisted of 5 turns of wire .208 cm. in diameter, wound in a spiral 46 cm. in diameter, with a pitch of 5.08 cm. The inductance of this part of the helix was 1.56×10^{-5} henrys. The primary part *P* of the helix consisted of 1.2 turns and had an inductance of $.151 \times 10^{-5}$ henrys. The condenser was made up of sheets of copper separated by miconite plates. The antenna, with dimensions marked, is shown in Fig. 186. The station sent out two waves, — one of wave length 153 meters and the other of wave length 129 meters.

For the purpose of determining what relative currents are

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[1] G. W. Pierce: Physical Review, Vol. 19, p. 196, 1904; Vol. 20, p. 220, 1905; Vol. 21, p. 367, 1905; Vol. 22, p. 159, 1906.

obtained in a receiving antenna, I set up an experimental receiving station at a distance of 550 feet from the sending station, and made some comparative measurements of the current received when various lengths of a single vertical wire (.208 cm. in diameter) were used as a receiving antenna. Provision was made for bringing the receiving antenna back into resonance with the incoming waves after each change of length of the antenna. This was done in two different ways: (1) by an inductance inserted in the antenna, and (2) by a shunt capacity; and since the law showing the relation of current to height of receiving antenna was different in the two cases, the two sets of results will both be briefly presented.

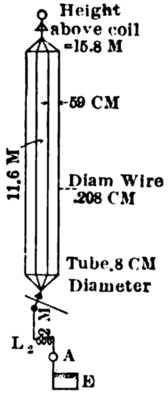

FIG. 186. Antenna of experiments on resonance.

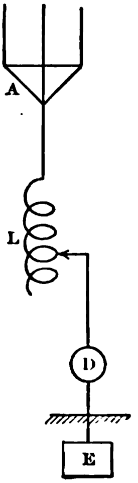

FIG. 187. Antenna with variable inductance for tuning.

Experiments on Received Current for Various Heights of Receiving Antenna, when Tuning was Effected by an Inductance in Antenna. — The form of receiving circuit employed in this case is shown in Fig. 187. The current-reading instrument shown at *D* was the high-frequency dynamometer described on page 113. It consisted of a minute coil of wire through which the oscillatory currents were passed; near this coil was suspended a small disc of silver. Oscillatory currents in the coil induced oscillations in the disc and caused the disc to deflect. The resistance of this instrument was only 1.33 ohms. Its inductance was 1.17×10^{-5} henrys.

The variable inductance used for tuning the circuit consisted of 51 turns of wire, .208 cm. in diameter, wound in a spiral on a vulcanite drum. Variations of inductance were made by turning the drum, and thereby causing a wheel-contact to move along the spiral. The inductance of the whole coil was 16.5×10^{-5} henrys, and the inductance of any fraction of the coil was accurately known.

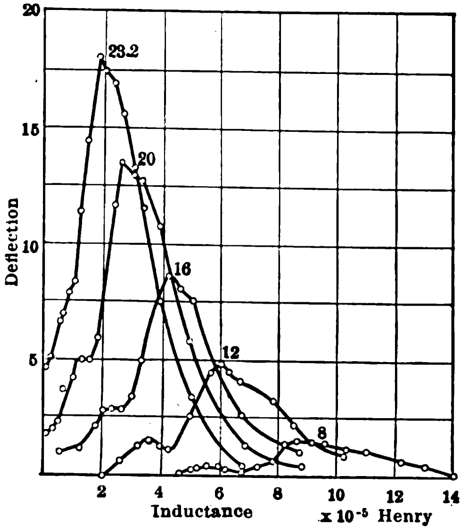

FIG. 188. Resonance curves with circuit of form of Fig. 187.

The results of a set of measurements are given in the curves of Fig. 188. The first curve, marked 23.2 at its vertex, was taken with a vertical receiving antenna 23.2 meters long (measured from the junction with the tuning coil). The different points on this curve were obtained as deflections of the dynamometer for different values of the inductance of the tuning coil. When the length of the receiving antenna was changed from 23.2 meters to 20 meters, the curve marked 20 at its vertex was obtained. In the same way the curves marked 16, 12 and 8 were obtained for lengths of antenna 16, 12 and 8 meters respectively.

Before discussing the results of this experiment I will present data obtained with a different form of receiving circuit.

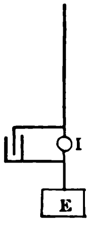

FIG. 189. Circuit for tuning with shunt capacity.

Similar Experiments with Shunt-Capacity Method of Tuning. — A diagram of this receiving circuit is shown in Fig. 189. An adjustable air condenser of known calibration in terms of capacity was placed in shunt to the receiving instrument, *I*, and by its use tuning was effected. Different lengths of receiving antenna were employed and the resonance curves of deflections against capacity were plotted. These are given in Fig. 190. The different curves correspond to the different heights of antenna as marked at the vertices of the curves.

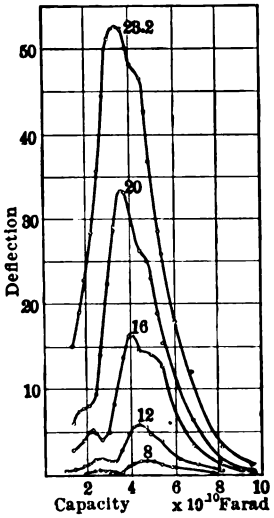

Fig. 190. Resonance curves with shunt-capacity tuning.

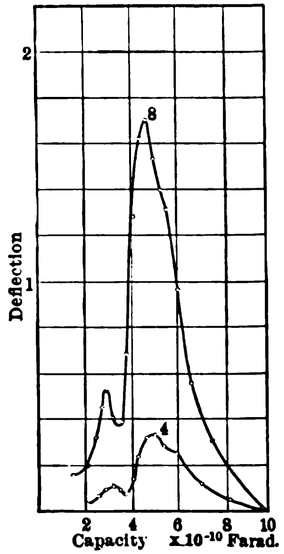

Fig. 191. Two of the curves on enlarged scale.

The curves taken with 8 meters and 4 meters of antenna are plotted separately in Fig. 191, where the scale of deflections is magnified 25 times.

On the Form of the Resonance Curves. — The two sets of curves taken with the two different methods of tuning show a marked similarity in form. The two maxima corresponding to the two different waves sent out from the transmitting station are clearly apparent. The irregularities near the summits, possessed in common by the two sets of curves, evidently belong to the wave produced at the sending station and are not characteristic of the receiving station. These irregularities could have been eliminated by a little more care in setting up the sending stations.

Comparison of Merits of the Two Methods of Tuning. — In passing, it is interesting to compare the strength of signals obtained with the shunt-capacity method of tuning with those obtained with the series-inductance method. The deflection at resonance for the two different methods of tuning, for different heights of antenna, are plotted in Fig. 192. The lower curve *A* was obtained with the inductance method of tuning; the curve *B*, with the shunt-capacity method. It is seen that the shunt-capacity method of tuning gives larger values. . In comparing these results numerically it should be remembered that the deflections of the instrument are proportional to the square of the current received.

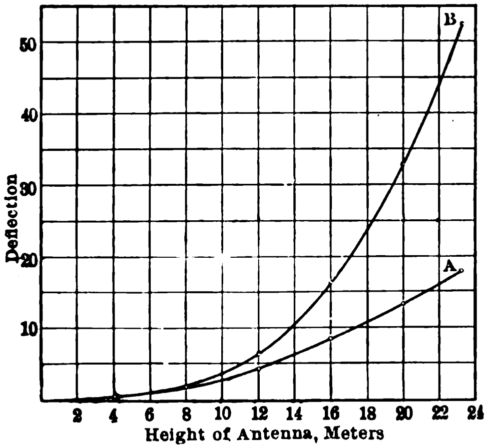

FIG. 192. Deflection as a function of the height of antenna. *A*, circuit tuned with series inductance; *B*, tuned with shunt capacity.

Relation of Received Current to Height of Receiving Antenna.— Coming now to the more important question as to the relation of received current to height of receiving antenna for each of the methods of tuning, we get the interesting result that the law is entirely different for the two different methods.

In order to make the relation apparent, the scale of the deflections was changed by a constant multiplier so as to make the deflection at 23.2 meters unity. The simplified relative deflections thus obtained, together with the square roots and the fourth roots of these deflections are plotted in Figs. 193 and 194. It is seen that in the series-inductance case (Fig. 193) the square-roots of the deflections lie on a straight line, while in the shunt-capacity case (Fig. 194) it is the fourth roots of the deflections that lie on a straight line.

Remembering that the deflections of the instrument are proportional to the square of the current, the results shown by the curves may be stated as follows:

I. The r.m.s. current in a vertical receiving antenna is proportional to the height of antenna, when this antenna is brought to resonance with incident waves by an appropriate inductance in series with the antenna.

II. The current in an inductive part of the circuit (the instrument) shunted with a capacity is proportional to the square of the height of the vertical receiving antenna, when the circuit is brought to resonance by appropriate adjustment of the shunt capacity.

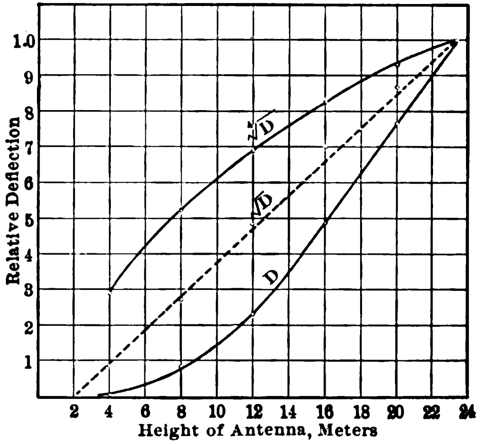

FIG. 193. Relation of received current to height of antenna when circuit is tuned by series inductance.

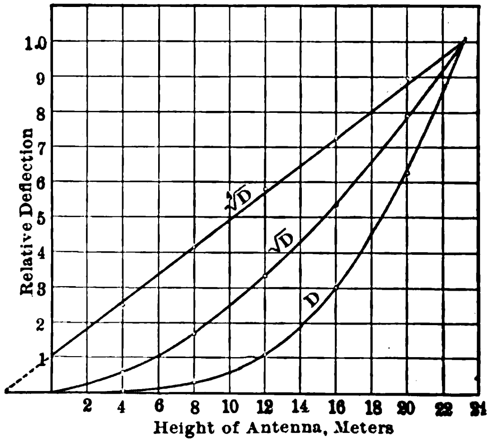

FIG. 194. Relation of received current to height of antenna when circuit is tuned by a shunt capacity.

These laws are only approximate, as shown by the fact that the straight lines in the two figures do not pass through the origin, as they should for an exact proportion. The reason of this departure from proportionality in the case of Law II may be found in the fact that the lengths of antenna were measured from the instrument to the top of the antenna. This leaves out of account the part of the antenna between the instrument and the ground, which amounted to 2 meters. This was also exposed to the action of the waves, and should perhaps be added to the height; this would make Law II almost an exact statement of the experimental result.

It is entirely possible that the relations I and II here stated may fail of verification when tested with greater heights of antenna. In the meanwhile the relations may be taken as fair approximations to the truth.

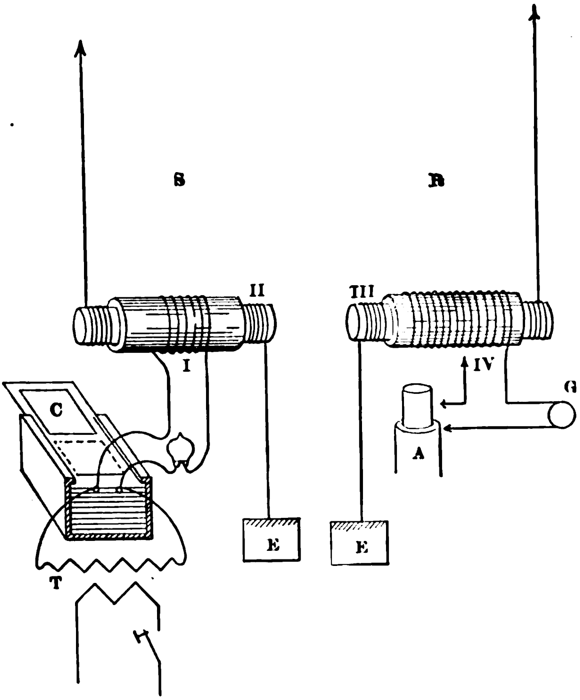

FIG. 195. Transmitting and receiving circuits for resonance experiments.

RESONANCE IN INDUCTIVELY COUPLED RECEIVING CIRCUIT

In the present experiments the inductively coupled type of circuits was employed at both the sending and the receiving stations. These circuits are shown in Fig. 195. It is seen that the complete system consists of four circuits, which shall be referred to in what follows as: I, the sending condenser circuit; II, the sending antenna circuit; III, the receiving antenna circuit; and IV, the receiving condenser circuit. The distance between the two stations is 187 meters across an open field. Antennæ 25 meters high could be used.

Coils. — Throughout these experiments the coils of the four circuits were kept constant and had the following dimensions:

Coil No.	No. of Turns.	Diameter of Wire, cm.	Length of Solenoid, cm.	Inductance, Henrys.
I.	9	.164		1.71×10^{-5}
II.	240	.104	46	125×10^{-5}
III.	240	.104	46	125×10^{-5}
IV.[1]	17	.164		7.04×10^{-6}

[1] Including the instrument.

Condensers. — The condensers at the two stations were adjustable. The condenser at the sending station was a glass-plate condenser, of which the number of plates could be varied. At the receiving station air condensers were used. They were four in number, made of concentric tubes of brass. The capacity in this circuit was varied by throwing in or out these air condensers as wholes or by varying any one of them by withdrawing the inner cylinder and reading on a scale the number of centimeters of length left overlapping. In the curves presented below, the capacity in the receiving condenser circuit IV, called "receiving capacity," is given in centimeters of cylinder overlapping in the air condensers — 1 cm. being equal to 2.77×10^{-11} farads.

Mercury Interrupter. — The oscillations at the sending station were produced by the discharge of the glass condenser through a Cooper Hewitt Mercury Interrupter.[1] The mercury interrupter was submerged in oil kept at 95° by an electric heater controlled by an automatic thermal regulator. It was shown in a previous research[2] that a mercury interrupter, in which no residual air was left, operated most effectively at that temperature.

Source of Current. — The source of current in these experiments was a step-up transformer operated on the 110-volt alter-

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[1] Pierce, Proc. Am. Acad. Arts and Sciences, Vol. 39, No. 18, Feb., 1904.

[2] Pierce, Physical Review, Vol. 19, p. 216.

nating electric light circuit. The secondary of the transformer was connected to the condenser *C*, Fig. 195. The switch in the primary was closed and opened automatically by a clockwork, so that the signals were sent every 35 seconds, without the aid of an assistant. Each signal lasted for 5 seconds, which was a little greater than the time required for reading the receiving instrument.

Receiving Instrument. — The receiving instrument, shown at *G*, Fig. 195, was again the high-frequency dynamometer (described on p. 113), with a resistance of 1.33 ohms. Such an instrument of low resistance does not materially modify the resonance conditions, so that the results obtained are the results for the circuits themselves. When these circuits are employed with the commercial detectors of high resistance, it is necessary to ascertain how far the resonance relations are modified by the detector. At present, however, we are concerned primarily with the resonant behavior of the circuits themselves.

Harmonic Oscillation. — The following experiment shows the possibility of harmonic resonance of the inductively coupled sending and receiving circuits. With the sending and receiving antennæ circuits of identical dimensions, different values were given to the capacity of the sending station, and resonance curves were taken by variations of the receiving capacity. The curves of Fig. 196 were obtained. Curves 1, 2, 3, . . . 7 were with 1, 2, 3, . . . 7 plates of condenser at the sending station. It is

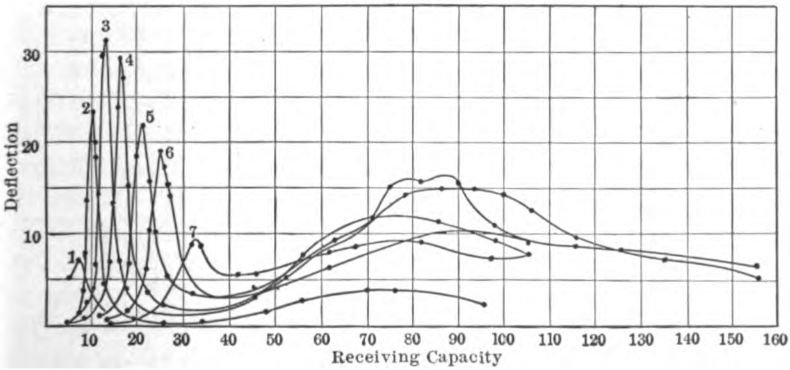

FIG. 196. Resonance curves obtained by taking readings of the dynamometer with various adjustments of the sending and receiving condensers.

seen that three plates, giving the resonance curve 3, appeared to constitute the most favorable conditions at the sending station.

But a close examination of Fig. 196 shows that there is a tendency of the resonance curves to rise again out in the region near "receiving capacity" 70; so it was thought advisable to go on

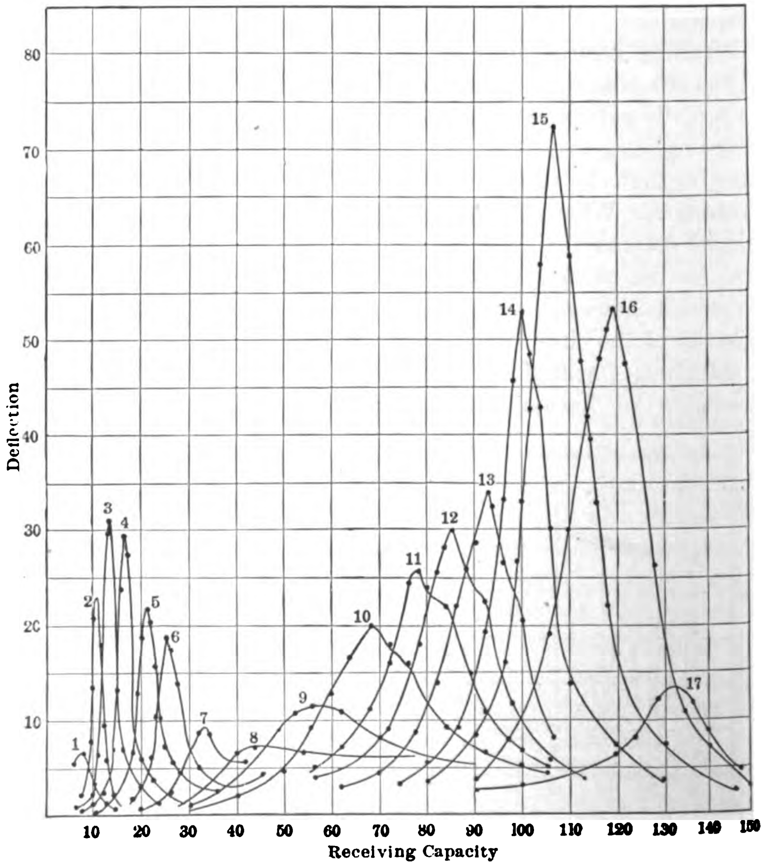

Fig. 197. Resonance curves showing the existence of harmonic oscillations.

increasing the capacity at the sending station. The result is shown in Fig. 197. Increasing the plates of sending condenser from 7 up to 17 disclosed the fact that a still better sending station results from the use of 15 plates of condenser at the sending station. That is, the sending station was a resonant station with either 3 or 15 plates in its condenser circuit. This was without any change in the antenna circuit. The reason is apparent. The 15 plates set the antenna vibrating with its fundamental period, while the 3 plates set the antenna vibrating as a first odd harmonic. The plates of the sending condenser were not all equal, so we must look to the receiving apparatus for a verification of this statement. This verification is evident from the optimum values of the resonant receiving capacity; namely, approximately 108 and 12, which are in the ratio of 9 to 1. These capacities being in the ratio of 9 to 1, the corresponding periods, which are proportional to the square root of the capacities, are in the ratio of 3 to 1, which is the ratio of fundamental to first odd harmonic.

This evidence of the possibility of a harmonic excitation of the sending antenna, and the harmonic response of the receiving antenna, shows the interesting analogy of the electrical apparatus to such acoustic apparatus as a closed organ pipe.

This experiment was performed with the receiving antenna circuit an exact duplicate of the sending antenna. For the purpose of obtaining information somewhat more general, it is proposed next to show some experiments with variations of the length of the receiving antenna, and to study the resulting effects on resonance.

Resonance Curves with Variation of the Length of Receiving Antenna. — The inductively coupled transmitting station *S* of Fig. 195 was employed to produce the waves. The sending antenna used was the four-wire antenna 15.8 meters long of Fig. 186. The sending condenser circuit was carefully adjusted to resonance with the antenna. The conditions at the sending station were kept constant.

At the receiving station, which was also inductively coupled (cf. *R*, Fig. 195), the coils of the inductive coupling were kept constant. The problem was to set up at the receiving station various heights of antenna, make various adjustments of the condenser in the side circuit and take readings of deflections of the dynamometer which is in the side circuit.

We have arriving at the receiving station waves of constant period and approximately constant intensity, and we are to seek the conditions under which the receiving instrument shows the largest readings. The variables are the height of the receiving antenna and the capacity of the air condenser, which is in the side circuit at the receiving station.

The receiving antenna of four wires was started at a height of 23.8 meters, measured from the coil in the mast circuit. The receiving antenna in this case was eight meters higher than the sending antenna. With this arrangement Curve 1, Fig. 198, was obtained by reading the deflections when the air condenser in the receiving side circuit was set at various values.

Next, the receiving antenna was shortened by cutting off 3 meters from the parallel portion, making the height 20.8 meters. Curve 2, Fig. 198, was obtained. Decreasing the length further to 17.8, 15.8, 14.8, 13.8 and 12.8 meters gave Curves 3, 4, 5, 6 and 7 respectively of Fig. 198. When the antenna was decreased one-half meter further, the deflections were smaller than those of curve 7, and increased slowly out to the limit of my available receiving capacity (180 cm. cyl.), so that the maximum could not be located.

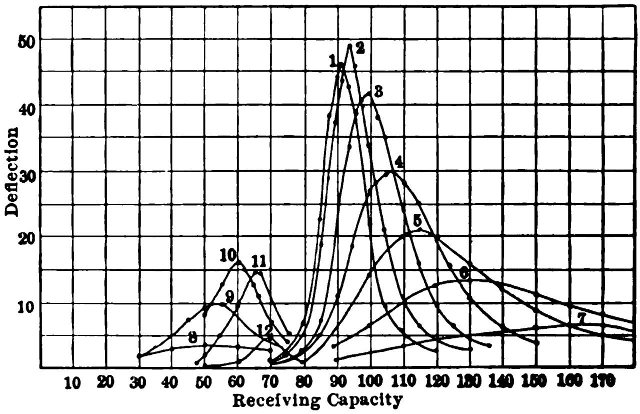

FIG. 198. Family of curves obtained by taking readings of the dynamometer with various lengths of receiving antenna.

With our attention fixed upon Curves 1 to 7 of Fig. 198 let us note a relation between the height of the antenna and the capacity required in the side circuit at the receiving station to produce resonance.

Empirical Equation for the Relation of H_a to C_4. — The above curves show that with a fixed frequency of incident waves, when the height of the receiving antenna H_a was *decreased*, it was necessary to *increase* the condenser capacity C_4 in order to obtain resonance.

To show quantitatively this effect Curve A, Fig. 199, was constructed with the resonant capacity in the receiving side circuit plotted horizontally and the height of the antenna plotted vertically. Curve *A* was found by trial to have approximately the equation

$$(H_a - 11.8)(C_4 - 84.6) = 88, \tag{a}$$

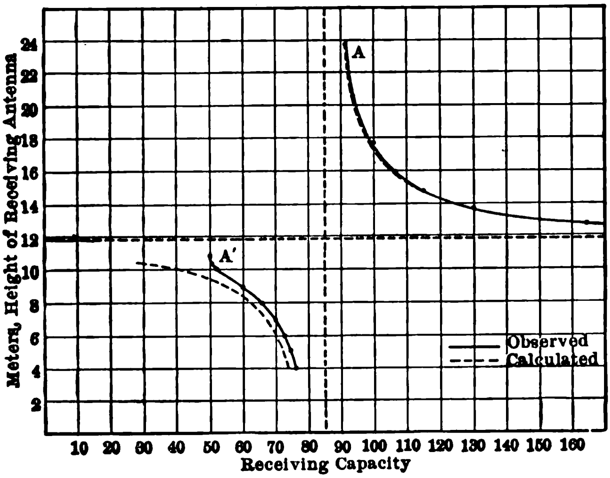

Fig. 199. Relation of resonant receiving capacity to height of receiving antenna.

as is shown by the following comparison of observed values, with values calculated from this equation (Table XIV):

TABLE XIV

RELATION BETWEEN HEIGHT OF RECEIVING ANTENNA AND RESONANT CAPACITY. FOUR WIRES RECEIVING

Curve No., Fig. 196.	Meters Antenna Above Coil, H_a.	Maximum Deflection, cm.	Resonant Capacity Observed, C_4	Resonant Capacity Calculated.
1	23.8	64	92	91.9
2	20.8	47	94	94.4
3	17.8	43	100	99.3
4	15.8	29.5	106	106.6
5	14.8	21	115	113.9
6	13.8	13	130	128.6
7	12.8	7.5	165	172.6

The only large difference between the observed and the calculated value of resonant capacity is in the case of Curve 7, where on account of the obtuseness of the experimental curve its maximum could not be accurately determined.

An examination of equation (*a*) shows that if we make H_a (height of receiving antenna) = 11.8 meters, C_4 would become infinite. This is the interesting fact that, with the particular fixed inductance coils employed in this experiment, if our equation is exact, no adjustment of the side condenser would enable us to receive any appreciable amount of current of the particular wave length arriving from the sending station. The experiment showed this to be approximately true, notwithstanding the fact that the receiving antenna, 11.8 meters of 4 wires, was not very different from the sending antenna, 15.8 meters of 4 wires.

Let us look at equation (*a*) again and suppose H_a to be less than 11.8. Let H_a be 10, then equation (*a*) shows that

$$\begin{aligned} -1.8\,(C_4 - 84.6) &= 88, \\ C_4 - 84.6 &= -49, \\ C_4 &= 35.6; \end{aligned}$$

that is, having lost resonance at $H_a = 11.8$, if we decrease H_a to 10 meters we ought to find the resonance again, but instead of finding it out near where we lost it (beyond $C_4 = 170$) the resonance ought to reappear at a comparatively small value of C_4. This was tried with the following result:

Search for the Other Branch of the Curve. — As the height of the four wires of the receiving antenna was decreased by small intervals below the values that gave Curve 7, Fig. 198, the deflections in the region of capacity between 90 and 180 became smaller and smaller, as if the resonant point were going away to infinity, and the deflections in the neighborhood of 50 began to grow, until when the height of the antenna was made 10.5 meters, a maximum became evident for about 50 cm. of the receiving condenser. The readings by which this maximum was obtained are plotted as Curve 8 in Fig. 198, along with Curves 1 to 7. Decreasing the height still further, Curves 9, 10, 11 and 12 were obtained with respectively 10, 9, 8 and 7 meters as the height of the antenna. These curves increase in intensity up to Curve 10 and fall off in 11 and 12. The five Curves 8 to 12 were taken with sensitiveness of the receiving instrument about five times as great as the sensitiveness used in taking Curves 1 to 7. Curves 8 to 12 in the left-hand group of Fig. 198 are plotted thus magnified five times in comparison with the group to the right, numbered 1 to 7.

The two groups when plotted with resonant receiving capacity against height of antenna form a curve of two branches A, A', Fig. 199. Values calculated from the equation (a) are plotted as the dotted lines in Fig. 199. The heavy curves are the observed values. From a comparison of the observed values with the computed values, we see that our equation, although it led us to look in the right direction for the resonance, is yet an imperfect equation. There are other terms in it beyond those here set down.

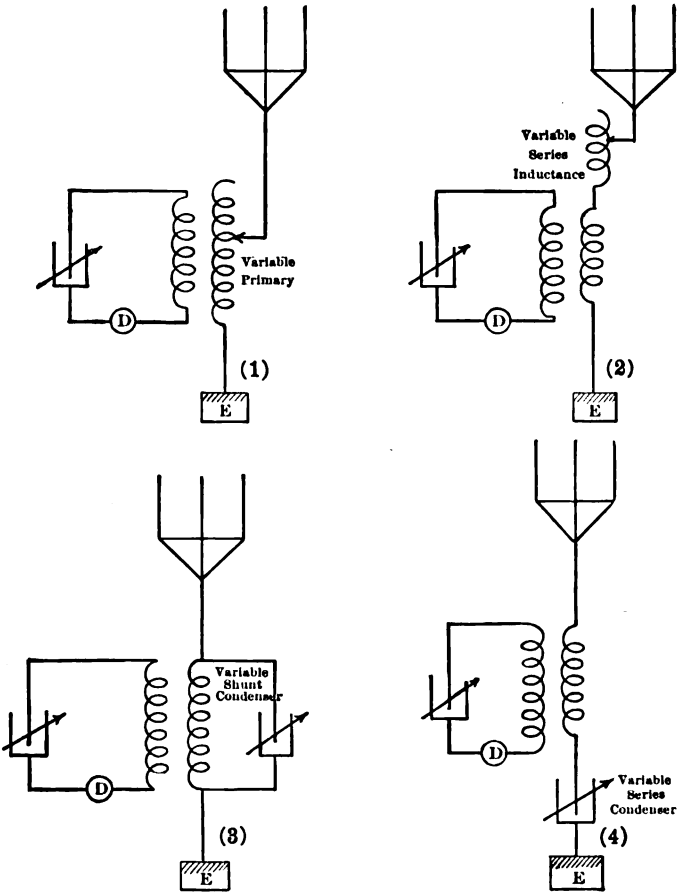

Fig. 200. Various types of inductively coupled receiving circuits.

Applicability of these Experimental Results to Practice. — One may ask, what is the use of this experiment in which the receiving transformer is kept constant and the length of antenna and the capacity of condenser in the receiving side circuit are varied, since we are not going to vary the length of antenna in actual practice? The answer is, that if we set up an antenna at random and depend upon variations of C_4 alone to get our resonance, we may have our antenna of a length (capacity) that bears to the waves we wish to receive the same relations that 11.8 meters of four wires bear to the waves of my experiment. In that case our tuning curve would correspond to Curve 7 of Fig. 198, and would give us very little current and very dull resonance. The remedy is: *Tune the antenna circuit as well as the side condenser.* This can be done by having (1) a variable primary of the receiving transformer or (2) a variable inductance in series with the primary, or (3) a variable condenser shunted about the primary, or (4) a variable condenser in series with the primary. The several methods are shown at (1), (2), (3), and (4) of Fig. 200, respectively. The methods (1), (2) and (3) permit an increase of the wave length of the antenna and adapt it to longer waves. The method (4) permits a decrease of the wave length of the antenna and adapts it to shorter waves. A very desirable arrangement is to combine all of these variables in one apparatus, as shown in Fig. 201. Then we can make such adjustments as are necessary for obtaining best resonance.

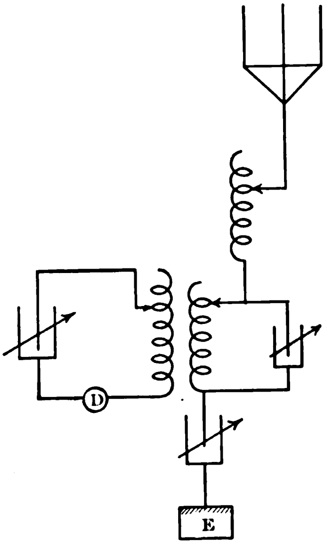

FIG. 201. An inductively coupled receiving station with several variable elements.

In order to see further the applicability of the experimental curves of Fig. 198, let us express in somewhat more general form the relation which we have given in the experimental equation (*a*).

Approximate Theoretical Equation for Resonance Relation at Inductively Coupled Receiving Station. — If we have a wave of wave length λ arriving at an inductively coupled receiving station of which the antenna circuit is adjusted to wave length λ_a, and the condenser circuit adjusted to wave length λ_c, then theory shows that the following is approximately[1] the relation between the several wave lengths in order to produce a maximum current in the condenser circuit:

$$\left(\frac{1}{\lambda_c^2}-\frac{1}{\lambda^2}\right)\left(\frac{1}{\lambda_a^2}-\frac{1}{\lambda^2}\right)=\frac{\tau^2}{\lambda^4}, \tag{1}$$

in which τ is the coefficient of coupling at the receiving station.

By a maximum current in the condenser circuit one or another of the maxima of the twelve different curves of Fig. 198 is meant. Not all of these maxima are equally strong, nor is the resonance for all of the maxima equally sharp. But for nearly any value of λ_a we can get a value of λ_c that will give resonance of a more or less pronounced character.

Let us try a few numerical examples that will make this clear. Let $\tau = .20$; and suppose waves are arriving of wave length $\lambda = 400$ meters. Suppose that our antenna wave length is set at $\lambda_a = 300$ meters. Then we have

$$\tau = .20,$$
$$\lambda = 400,$$
$$\lambda_a = 300,$$

to determine λ_c. With these numerical values equation (1) becomes

$$\left\{\frac{1}{\lambda_c^2}-\frac{1}{(400)^2}\right\}\left\{\frac{1}{(300)^2}-\frac{1}{(400)^2}\right\}=\frac{(0.20)^2}{(400)^4}.$$

Multiplying by $(400)^4$ we get

$$\left(\frac{400^2}{\lambda_c^2}-1\right)\left(\frac{400^2}{300^2}-1\right)=.04.$$

Whence $\lambda_c = 390$ meters. This 390 meters is the wave length at which we must set our receiving condenser (in a coupled circuit) in order to receive a 400-meter wave, provided our antenna is set for a 300-meter wave.

Carrying through similar computations for other values of the wave length of the incident waves we obtain the results recorded in Table XV.

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[1] In the derivation of this formula the small effect of resistance on the wave length was neglected; also the capacity of the antenna was considered localized instead of distributed. The formula (of which our equation (*a*) is a special case) is, therefore, inexact, but will serve to illustrate some interesting facts about the tuning of a receiving station.

TABLE XV

RESONANT WAVE LENGTH ADJUSTMENT OF THE CONDENSER SIDE-CIRCUIT WHEN THE ANTENNA IS KEPT FIXED AT WAVE LENGTH $\lambda_a = 300$ METERS

Wave Length of Incident Waves λ.	Resonant Value of Receiving Condenser in Wave Length, λ_c.
100	103
200	210
250	267
280	330
290	430
300	...
310	207
330	302
350	332
400	390
500	493
600	598

The formula does not apply to the case of $\lambda = 300$ meters, so this value is omitted from the calculations.

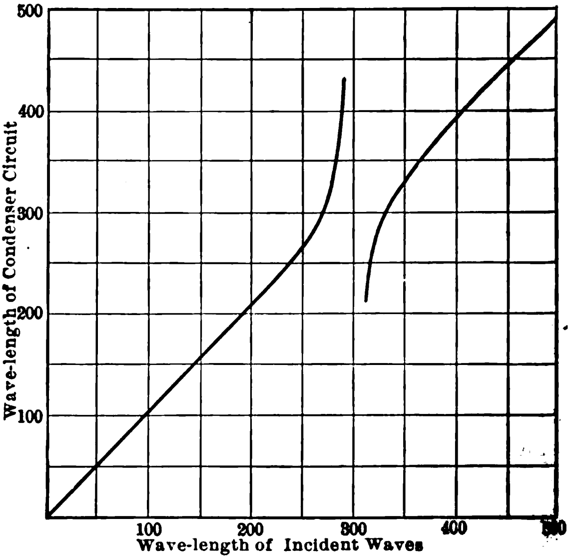

FIG. 202. Curves showing resonant adjustment of wave length of the condenser circuit for different values of incident waves, — the antenna wave length being fixed at 300 meters.

The results recorded in Table XV are shown graphically in Fig. 202.

This curve shows several facts of interest. It shows, for example, that when we have been receiving a wave length slightly shorter than our antenna wave length, and a wave comes in slightly longer than our antenna wave, we must actually decrease our receiving capacity to bring the longer wave into resonance. It shows also that any particular adjustment of our receiving capacity is resonant for two different waves. For example, with our antenna set at wave length 300 meters, and our condenser circuit set for 400 meters, we are really in tune for either a 290-meter wave or a 410-meter wave, not in the best tune, it is true, but sufficiently in tune to be disturbed if the interfering signals are strong.

Advantage of Varying Coefficient of Coupling in Tuning. — There are times when we wish to be in tune for two wave lengths at once, because the station we are receiving usually sends out two waves at once. If we set our receiving condenser at 300 meters, we are in tune for a 270-meter and a 330-meter wave, and these might well be sent out by the same station. They will in fact be sent out by the same station, if it has the same coefficient of coupling as our receiving station, $\tau = .20$, and has its condenser circuit and antenna circuit tuned to 300 meters.

This suggests an important improvement in our tuning mechanism at the receiving station; namely, a device by which we can change the coefficient of coupling at the receiving station and thus make the receiving coefficient of coupling identical with the coefficient of coupling of any particular station we wish to receive. This device[1] is employed in many of the recent receiving sets, and consists of an adjustment by which the primary coil of the receiving transformer may be either moved away from or rotated with respect to the secondary coil. The same result can be attained by cutting out inductance in the primary of the transformer and putting it in series where it will not be in inductive relation with the secondary coil.

Effect of Variation of the Coefficient of Coupling on Sharpness of Resonance and on Received Energy. — Theory shows that diminution of the coefficient of coupling increases the sharpness of resonance. At the same time this diminution of coefficient of coupling brings with it a decrease of energy. I tried some experiments to see what improvement in sharpness of resonance we might

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[1] On account of the high resistance of the detectors the proper adjustment of the coefficient of coupling is not one of exact equality with the coefficient of coupling of the sending station, but must be determined by trial.

attain by this method. With the very low-resistance dynamometer as a measuring instrument, the curves of Fig. 203 were obtained, with coefficients of coupling at the receiving station equal to .30 and .07 respectively. The energy received in the former case was twenty times as great as in the latter case; but to compare sharpness of resonance the two curves are both plotted with amplitude 100.

With τ = .30 the deflection falls to half for a change of condenser capacity of 5%, while with τ = .07 the deflection falls to half for a change of capacity of 2.5%. The deflection is proportional to the energy, and the capacity is proportional to the square of the wave length, so we may say that the energy received falls to half for a variation of 2.5% and 1.25% of the wave length in the two cases.

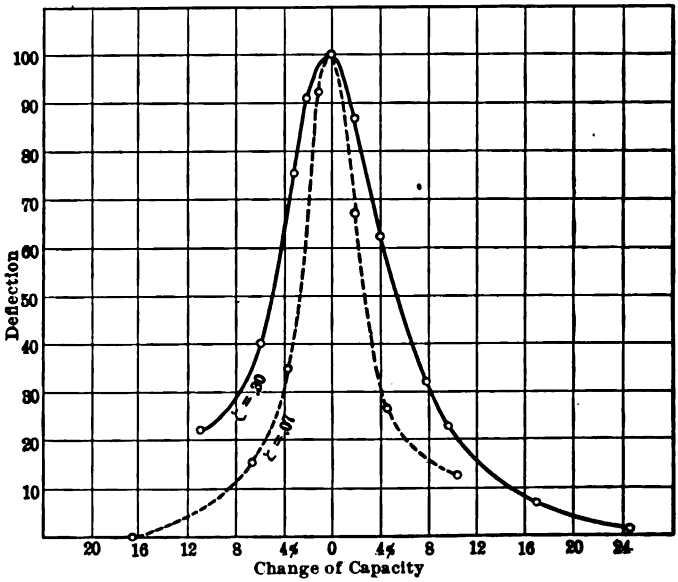

FIG. 203. Sharpness of resonance for two different values of τ, the coefficient of coupling.

The experiment thus confirms the theoretical deduction that with a decrease of the coefficient of coupling the sharpness of resonance is increased. The gain in sharpness of resonance is, however, paid for in loss of energy, — the energy received with τ = .07 being $\frac{1}{20}$ of the energy received with τ = .30.

EFFECT OF RESISTANCE OF DETECTOR ON RESONANCE IN COUPLED WIRELESS TELEGRAPH CIRCUITS

Although the coefficient of coupling of the coupled circuits influences somewhat the sharpness of resonance, a far greater influence in the case of the practical stations is exercised by the resistance of the detectors which are used in the reception of the signals. These detectors, when sufficiently sensitive to respond to weak signals, have a very high resistance. We have seen in Fig. 150 (p. 226) how a high resistance inserted in a simple circuit consisting of a condenser in series with an inductance renders the resonance dull. With the coupled circuits the effects are somewhat more difficult to present, and it is necessary to examine the resonance curves obtained by varying both the antenna wave length and the condenser-circuit wave length in order to ascertain the influence of resistance on the sharpness of resonance.

I have submitted the problem to a mathematical examination, and without giving the steps of the reasoning, I take the liberty of presenting some of the results. The form of receiving circuits to which the discussion applies is shown in Fig. 204. The following constants of the circuits were assumed in the computations:

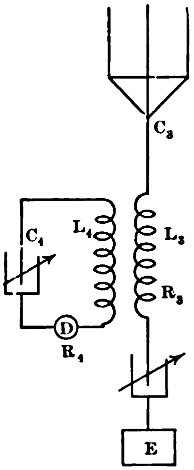

Fig. 204. Diagram of circuit providing for variation of wave length of primary and secondary by variable condensers.

L_3 = Self-inductance of the antenna circuit = $.3 \times 10^{-3}$ henry,

L_4 = Self-inductance of the condenser circuit = $.5 \times 10^{-3}$ henry,

M = Mutual Inductance = $.2 \times 10^{-3}$ henry.

τ^2 = Square of coefficient of coupling = .267,

λ = wave length of incoming waves = 472 meters.

The antenna circuit was given various resistances, R_3, and the condenser circuit various resistances, R_4. The resistance R_4 resides chiefly in the detector, and the resistance R_3 includes the apparent resistance due to distributed capacity in the antenna.

The incoming waves were supposed to be a persistent train of undamped waves.

Computations were made for two cases: I, When we fix the antenna adjustments at their best values, and tune with C_4;

II, When we fix C_4 at its best value, and tune by adjustments of the antenna circuit. The appropriate adjustments for the two cases and the sharpness of resonance obtained depend in an intimate way upon the values of R_3 and R_4. The results for the two cases are here briefly presented.

Case I. R_3 = 10 Ohms, R_1 = 64,000 Ohms. — Reference is made to the curve marked "$R_4 = 64{,}000$" in Fig. 205. This curve is entirely flat on top, and shows that, with a detector of resistance 64,000 ohms used in a circuit with the constants we have assumed, there is no possibility of discriminating between different wave lengths by any adjustment of the condenser C_4. In this case we may as well leave C_4 set at any value above that which with the inductance L_4 gives 200 meters. It is then equally ready to detect all wave lengths.

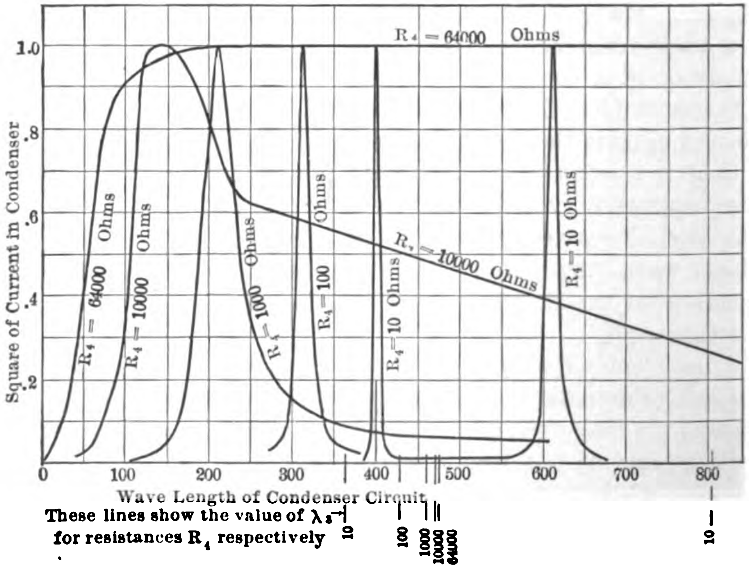

Fig. 205. Curves showing effect of resistance R_4 on resonance with a coupled system of circuits tuned by adjusting C_4. Wave length of incident waves = 472 meters.

In this case the calculations show that the antenna circuit must be adjusted to the wave length to be received; namely, 472 meters in the numerical example under consideration. I have attempted to indicate this fact in the diagram by drawing a line across the wave-length scale at 472 meters and marking it 64,000 ohms.

Case I (Continued). $R_3 = 10$ Ohms, $R_4 = 10{,}000$ Ohms. — Suppose, now, that the detector should have 10,000 ohms resistance instead of 64,000 ohms. With this reduced resistance the curve marked " $R_4 = 10{,}000$ " is obtained. With this value of R_4, tuning by the condenser C_4 is possible, but the resonance is dull as is indicated by the obtuseness of the curve.

Appropriate adjustment of the antenna in this case is at the line marked "10,000" on the bottom margin; namely, $\lambda_3 = 470$ meters.

Case I (Continued). $R_3 = 10$ Ohms, $R_4 = 1000$ Ohms. — The curve marked " $R_4 = 1000$ " is obtained; and the antenna must be shifted to the line on the bottom margin marked "1000"; that is, the antenna wave length must be set at 460 meters for best resonance. The resonance curve " $R_4 = 1000$ " is much sharper than those obtainable with the higher resistances.

Case I (Continued). $R_3 = 10$ Ohms, $R_4 = 100$ Ohms. — Reference is made to the curve marked " $R_4 = 100$," and to the line at the bottom margin marked " 100." The resonance is sharper than with the higher resistances, and the appropriate adjustment of antenna wave length has shifted to $\lambda_3 = 430$ meters.

Case I (Concluded). $R_3 = 10$ Ohms, $R_4 = 10$ Ohms. — Two resonance positions appear in this case: one at 400 meters (wave length of the condenser circuit), with appropriate adjustment of antenna at 360 meters; and the other at 610 meters (condenser circuit), with antenna adjustment at 810 meters. The resonance here is extremely sharp, especially for the adjustment of condenser C_4 in the neighborhood of 400 meters.

Case II. Let us now suppose a detector circuit of resistance 10,000 ohms, and let us set the condenser C_4 of this detector circuit at its resonant value in the neighborhood of 135 meters (see the diagram for Case I), and then tune with the antenna circuit; for example, by varying the condenser C_3. The results are given in Fig. 206, the different curves corresponding to different values of R_3 in the antenna circuit. From these curves it will be seen that even with a high-resistance detector ($R_4 = 10{,}000$ ohms) the tuning in the antenna circuit is sharp, provided the antenna effective resistance is low (curve marked " $R_3 = 10$ "). With increase of antenna resistance the resonance becomes less sharp.

In practice with a system of coupled circuits like that under discussion and with the high-resistance detectors in use, it is difficult to realize sharper resonance than that shown in the curve marked "$R_3 = 50$." This is obtained by tuning with the adjustment of the antenna circuit. These curves shift almost uniformly with wave length, so that if a number of stations are sending simultaneously, the series of resonance curves obtained would be like that of Fig. 207.

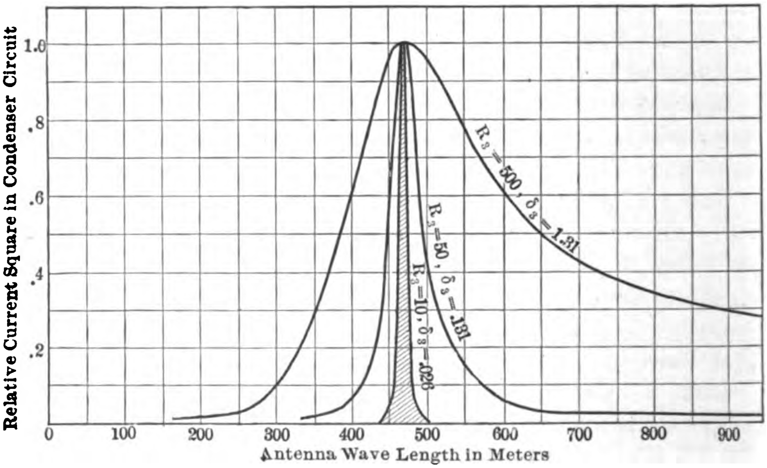

FIG. 206. Curves showing effect of resistance R_3 on resonance with a coupled system tuned by adjusting C_3.

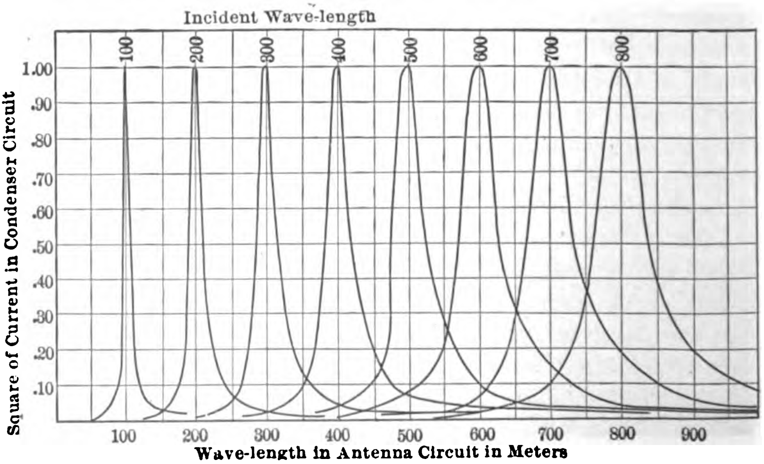

FIG. 207. Curves showing the extent of interference in a computed case of coupled circuits.

These curves are computed with what seems to be about the conditions obtaining in good practice. It is seen by a reference to Fig. 207 that if a receiving station is attuned for a 500-meter wave, it will receive also about 7% as much energy from a 400-meter or a 600-meter wave as it does from the 500-meter wave. From a station emitting a 300-meter or a 700-meter wave the disturbing energy will amount to about 2% of the energy received from the 500-meter wave; while from a sending station emitting a 200-meter or a 800-meter wave the disturbing energy will be below 1%. These statements are on the assumption that all of the stations would give the same received energy if the receiving station were in tune for them.

These computations, although not claiming to be highly accurate, will give a crude idea of about the extent to which interference can be prevented by the use of the coupled circuits consisting of a condenser circuit containing the receiving instrument inductively or directly coupled to an antenna circuit.

There are other methods of coupling receiving circuits to prevent interference which will attain better discrimination between desired and undesired signals, but these almost always greatly reduce the intensity of signals, and cannot be employed for the reception of signals from stations at a great distance from the receiving station.

CHAPTER XXV

DIRECTED WIRELESS TELEGRAPHY

For some purposes it is desirable to send electric waves away in all horizontal directions from the sending station, and to receive electric waves coming in from any direction. This is the general mode of propagation of the electric waves, and permits, for example, the establishment of communication with a vessel in an unknown location at sea.

Such a general diffusion of waves is, on the other hand, often very undesirable for the following reasons: (1) It is wasteful of transmitted energy; (2) the message may be received by an enemy or an unfriendly neighbor who could generally be prevented from receiving it if we could direct the waves; (3) when we wish to communicate in one direction we may unnecessarily disturb or be disturbed by an operating station in another direction; (4) if the receiving apparatus can be made to respond selectively to electric waves from different directions, a vessel at sea can get its bearings and position by finding its direction from two different known stations. For these and other reasons, several inventors have given attention to the problem of emitting or receiving electric waves directively and have made some progress toward a solution.

Hertz's Parabolic Metallic Reflectors. — As was pointed out in Chapter XII, Marconi in his early experiments tried to use parabolic metallic reflectors about his oscillator and receiver, for the purpose of transmitting or receiving in a given direction. On account of the difficulty of constructing and sustaining mirrors sufficiently large to have proper proportions to the wave lengths required, this device has not been successfully used in practice.

Braun's Parabolic Oscillator. — In 1902, Ferdinand Braun[1] proposed the use of an oscillator consisting of several elements which were arranged to compose a parabolic surface. A diagram of this form of oscillator is shown in Fig. 208. Several vertical metallic strips A_1, A_2, A_3 . . . were arranged to lie in a para-

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[1] U. S. Patent, No. 744,897, filed Feb. 19, 1902, issued Nov. 24, 1903.

bolic cylindrical surface and were connected to a spark terminal S_1. Another similar set of strips B_1, B_2, B_3 . . . below the first set were also provided with a spark terminal S_2. The oscillations are produced by a discharge across the spark gap S_1S_2. This arrangement, which, according to the inventor, would send out electric waves in one direction, does not seem to have met with practical success.

Braun's Phase-difference Oscillator. — Another method proposed by Ferdinand Braun[1] makes use of two or more vertical oscillators at certain distances apart provided with means of exciting in the oscillators waves suitably differing in phase. For example, if the two antennæ A and B, Fig. 209, are one half wave length apart, and if the oscillations in the two antennæ are opposite in phase, the two sets of waves sent out will add in directions in the plane of the two antennæ and will neutralize each other in a direction at right angles to this plane.

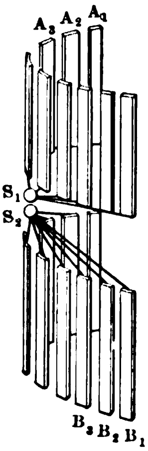

FIG. 208. Braun's parabolic oscillator.

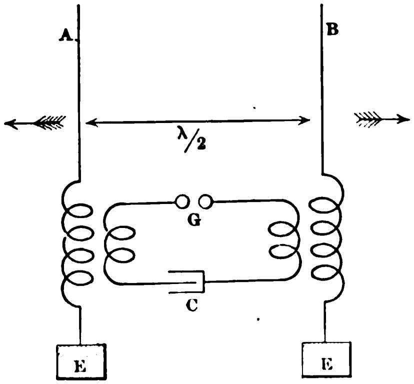

FIG. 209. Braun's phase-difference oscillator for directed wireless telegraphy.

Suitable phase difference in the antennæ may be partially attained by the use of a condenser circuit coupled with the antennæ, as shown in Fig. 209. With this arrangement the problem is, however, complicated by the occurrence of oscillations of double periodicity. This difficulty has been removed in a very

[1] U. S. Patent, No. 776,380, filed July 26, 1904, issued Nov. 29, 1904.

interesting method of excitation devised, at Professor Braun's suggestion, by Messrs. Mandelstam and Papalexi, and is described in *Physikalische Zeitschrift*, Vol. 7, p. 302, 1906, to which the reader is referred.

With three or more antennæ suitably differing in their phase of excitation and situated at the vertices of a triangle or of a polygon, any one of several directions may be selected as the direction of strongest transmission. In a similar way, by employing receiving stations provided with a multiplicity of antennæ separated by suitable fractions of a wave length, and by using proper means of combining the impulses in a secondary detector circuit, some selectivity of direction from which the waves are received can be attained.

Marconi's Directive Antenna. — In 1906 Mr. Marconi presented to the Royal Society an account of some experiments which showed that an antenna having a short vertical part and then extending away to a considerable distance in a horizontal direction, as shown in Fig. 210, emitted electric waves most strongly in the direction *D* away from which the free end of the antenna points.

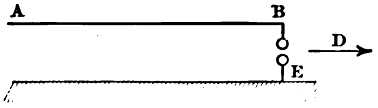

Fig. 210. Marconi's directive antenna.

Marconi's experiments showed for a given distance between the receiving station and the transmitting station the relative intensities in different directions which, plotted in polar coördinates, give a curve of the form of Fig. 211. In this figure the relative intensities in different directions are the lengths of the radii drawn from the origin to the curve.

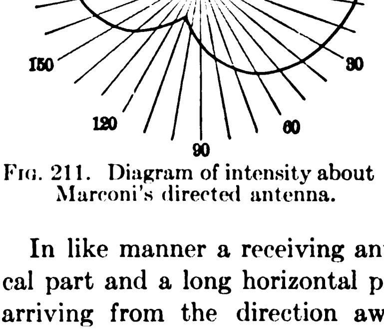

Fig. 211. Diagram of intensity about Marconi's directed antenna.

In like manner a receiving antenna consisting of a short vertical part and a long horizontal part receives more strongly waves arriving from the direction away from which the open end of the antenna points. Mr. Marconi has utilized this principle in the construction of his powerful stations at Wellfleet and at Poldhu.

Explanation of Directive Radiation from Marconi's Bent Antenna. — Professor Fleming,[1] Dr. Uller,[2] Dr. Zenneck,[3] and others, have given explanations of the cause of the directive radiation from the Marconi horizontal antenna. All of these writers employ the theory of images as a starting point, by which means the antenna and ground connection of Fig. 210 is replaceable by the equivalent system of Fig. 212.

Fleming's Explanation. — In further explanation, Professor Fleming takes a rectangular circuit of the form shown in Fig. 213, and imagines a current flowing around the rectangle in the direction of the arrows. This current creates a magnetic field, the direction of which along the surface of the earth is at right angles to the plane of the paper; and at equal distances from the center, the magnetic force represented by H is toward the spectator on both sides. Now, suppose a wire EF equal in length to one side of the rectangle to be placed contiguous to one vertical side, and to carry a current opposite in direction to that in the side of the rectangle (left hand) to which it is in proximity; then the magnetic field of this straight current is h' *from* the spectator on the left-hand and h *toward* the spectator on the right-hand side. Accordingly, the total field $H + h$ on the right is greater than the total field $H - h'$ on the left, because, according to Professor Fleming, the individual fields are added on one side and subtracted on the other. Now, since the two oppositely directed currents in the

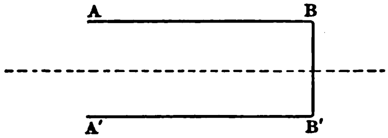

FIG. 212. Marconi directed antenna and its image.

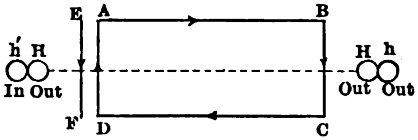

FIG. 213. Diagram used by Professor Fleming in explanation of the directive action of the Marconi bent antenna.

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[1] J. Fleming: Phil. Mag., Vol. 12, p. 588–604, 1906.
[2] Carl Uller: Phys. Zeitsch., Vol. 8, p. 193, 1907.
[3] J. Zenneck: Phys. Zeitsch., Vol. 9, p. 553, 1908.

adjacent wires may be imagined to come so close together as to annul each other, the effect is the same as if a circuit of parts *ABCD* were used with the parts *AD* and *EF* omitted.

Objections to Professor Fleming's Explanation. — It appears that serious objection can be raised to Professor Fleming's explanation as follows: He does not take into account the mode of vibration of the oscillator, nor does he take account of the time required for the magnetic field to travel from the radiating system to the point under consideration. In the case of the field *HH* produced by the closed rectangular circuit, the time to travel to the right and to the left to the points under examination will be the same, and the two *H*'s will be equal and in the same direction, as Professor Fleming explains, only provided the same current flows in every part of the loop. No such uniform flow of current occurs in the case of the actual oscillation. Also, in the case of the forces h and h' the distances from *EF* are unequal, and therefore the times to travel to the points under examination are not the same, and whether the fields h and h' will be opposite to each other or not depends on the mode of vibration of the two oscillators and the time for the waves to travel to the points under examination. The whole question of the relative strength of waves emitted in the two opposite directions is avoided by Professor Fleming because of his substitution of a system that can never represent the actual system; and after we have examined Professor Fleming's reasoning the solution of the actual problem is still completely in doubt.

Explanation of Dr. Uller. — Professor Fleming[1] had earlier employed a different method of attacking the problem directly by imagining the form of the electric field of force about the directive antenna. This method was revived in 1907 by Dr. Uller, who pictured the field of electric force about the Marconi oscillator in the form given in Fig. 214. The upper half of this diagram would represent the mode of propagation of the waves over the surface of a good conducting plane. Where the surface of the earth is not a good conductor, the electric force would be inclined near the surface, as has been shown in Chapter XV, and would give a field of force slightly different from that here represented.

Zenneck's Explanation. — Zenneck has modified the theory of Uller so as to take further into account the effect of imperfect conductivity of the earth's surface. As we have seen in

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[1] Fleming: Electric Wave Telegraphy, p. 627, 1906.

Chapter XV, the electric force at the surface of the earth, where-ever it is not a good conductor, leans forward, so that we can ascribe to the electric force in a particular case a mean direction, *E*, Fig. 215. Now the direction of propagation is perpendicular to *E*; i.e., in the direction *S*, whence there is penetration of the energy into the earth's surface and a consequent absorption, so that the distant receiving station is reached by the energy that started in the direction *AX*, Fig. 216, and not by the energy that started along the surface of the earth. By examination of Fig.

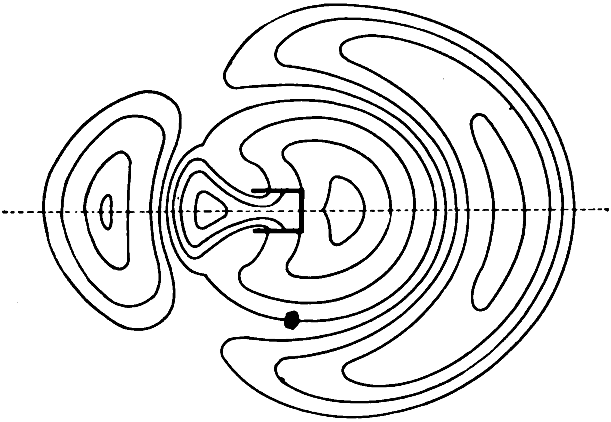

Fig. 214. Dr. Uller's diagram of field of electric force about the bent antenna.

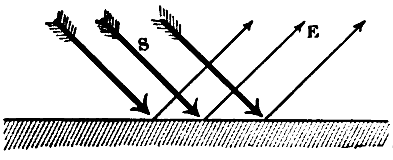

Fig. 215. Diagram used by Dr. Zenneck in explaining directed wireless telegraphy.

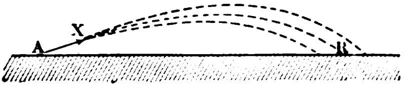

Fig. 216. Zenneck's diagram showing the course of the radiation from *A* to *R*.

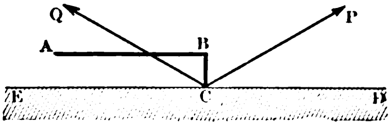

Fig. 217. Diagram applying to Zenneck's explanation.

214 it will be seen that a bent antenna of the form of *ABC*, Fig. 217, radiates more energy in the direction *CP* than in the direction *CQ*, and therefore attains a greater distance in the direction *CD* than in the direction *CE*. This explanation of Zenneck would indicate that the directive effect of the bent antenna is much greater over land than over sea. I do not know of any experimental confirmation of this deduction.

These explanations are lacking in quantitativeness, but taken together serve to give a tentative reconciliation of some of the experiments with theory.

Bellini and Tosi's Directive Apparatus. — A very ingenious method of directively transmitting and receiving electric-wave signals has been devised by Messrs. Bellini and Tosi.[1] A diagram of a receiving station embodying their invention is shown in Fig. 218. The directive aerial system consists of two closed or nearly closed oscillation circuits of triangular shape *ABBA* and $A^1B^1B^1A^1$ arranged respectively in two perpendicular planes. These two antenna circuits contain respectively the coils *m* and *n*, which may be circular coils, and are perpendicular to each other with their windings in the planes of the antenna circuits respectively. A third coil *s* connected to a wave detector and a condenser *c* is

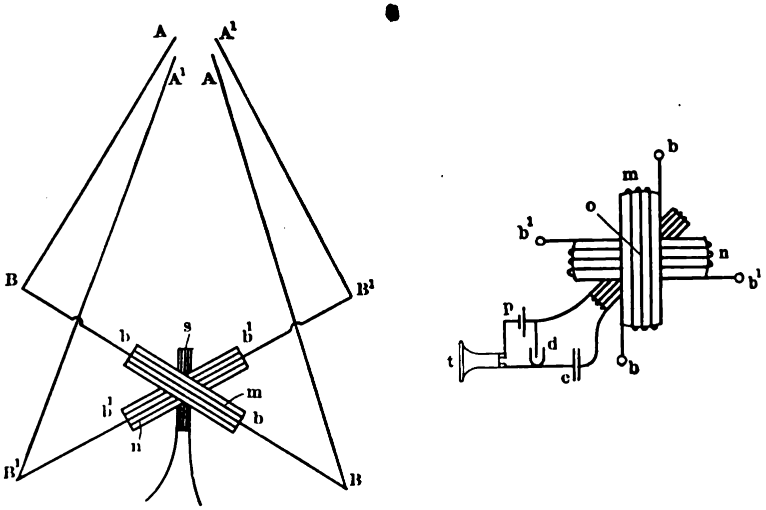

FIG. 218. Bellini and Tosi's directive apparatus.

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[1] U. S. Patent, No. 945,440, filed Oct. 1, 1907, issued Jan. 4, 1910.

placed within the two coils *m* and *n* and is capable of rotation about an axis through *o*.

Electric waves coming from any particular direction produce oscillation in the two antenna circuits with intensities respectively dependent on the direction from which the waves come. The oscillations thus set up, passing through the coils *m* and *n*, compound to form a single magnetic field with a direction perpendicular to that from which the waves come. The strength of the induced current in the movable coil *s* will depend on its orientation with respect to the resultant magnetic field, and will be a maximum when the coil *s* is in a position to embrace as many as possible of the lines of magnetic force. This optimum direction is perpendicular to the field, and therefore parallel to the direction from which the waves are coming.

It is therefore possible to determine the direction from which the waves are arriving by merely providing the rotating coil *s* with a pointer in its own plane. When a maximum strength of signals is received the pointer is directed either toward or away from the signaling station. The final ambiguity as to whether the signaling station is in the direction of the pointer or in the opposite direction would have to be removed by some additional general knowledge of the probable location.

A sending station, devised also by Bellini and Tosi, and capable of directively transmitting signals, consists of a similar aerial system and a similarly rotatable interior coil. The latter is, however, connected with a discharge condenser instead of with the receiving mechanism. The processes involved are, then, the reverse of those entering into the receiving apparatus.

Limitations of Directive Wireless Telegraphy. — The several directive devices above described act directively only in a general way; that is, some more energy is sent in one direction than in other directions, but there is still a considerable diffusion of energy in all directions. The economy effected in the energy of transmission does not seem to be very great, particularly because the closed loops, or nearly closed loops, are not such good radiators or receivers as the straight vertical antenna. However, whenever the bent antenna is installed in land stations the orientation to effect maximum transmission in the most useful direction is generally chosen. Also, it has been proved to be entirely possible with each of the principal systems to determine the direction of the receiving station from the sending station. This achievement does not seem to have been of sufficient importance up to the present to warrant special installations for the purpose. It is, however, entirely possible that greater attention will be given to this subject when the art of wireless telegraphy, which is now embarrassed by novelty in so many directions, shall have become a little more standardized in its fundamental requirements.

CHAPTER XXVI

WIRELESS TELEPHONY

Sketch of the Method of Wireless Telephony by Electric Waves. — The circuits employed in wireless telephony by electric waves resemble very closely those used in wireless telegraphy.

The transmitting apparatus for wireless telephony makes use of a persistent train of electric waves of high frequency sent out from an antenna. Instead of interrupting these electric waves by a key, as in telegraphy, modifications by the voice, corresponding to spoken words, are impressed upon them. These modifications by the voice are applied to the electric waves by means of a carbon transmitter, or similar instrument, placed in the sending circuit or connected with it.

The receiving apparatus is indentical with that employed in wireless telegraphy, and makes use of a receiving antenna coupled with a circuit containing some type of rectifying detector; e.g., an electrolytic detector, a crystal-contact detector, or a vacuum-tube rectifier. About the detector is shunted a sensitive telephone receiver.

The action is as follows: If an unmodified train of electric waves having a frequency higher than the limit of human audibility (35,000 vibrations per second) arrives at the receiving station, the receiving circuit, if properly tuned, will sustain electric oscillations which, passing through the detector, will be rectified and will give a series of rectified impulses to the receiving telephone circuit. These impulses, being all in one direction, will act as a continuous pull on the telephone diaphragm, — a continuous pull for the reason that the diaphragm cannot follow the rapid successive impulses, and because also, on account of the inductance of the telephone circuit, these impulses are modified electrically into a practically continuous current through the receiver.

Having in mind that a continuous train of high-frequency waves produces a continuous pull on the receiving telephone diaphragm, let us now suppose that words are spoken into a carbon transmitter at the sending station in such a manner as to modify the emitted train of waves. These modifications of the emitted waves will produce corresponding modifications in the pull on the telephone diaphragm at the receiving station, so that the receiving diaphragm will execute vibrations similar to those of the transmitting diaphragm, as in ordinary telephony over wires.

Methods of Producing the Persistent Train of Waves. — Some of the details of the process will now be presented. To produce the persistent train of oscillations several methods are available, of which three will be mentioned, to wit: 1. The Singing-arc Method; 2. The High-frequency Alternator Method; 3. The Mercury-arc Method.

The first of these methods has been described in the preceding chapter. A brief description of the other two methods follows.

The High-frequency Alternator Method of Producing Sustained Oscillations. — In 1901, Professor R. A. Fessenden[1] applied for a patent for " improvements in apparatus for the wireless transmission of electromagnetic waves, said improvements relating more especially to the transmission and reproduction of words or other audible signals." A diagram of the simple apparatus described in this application is shown as Fig. 219.

In the diagram, which represents the transmitting station, *D* is an alternating-current generator of high periodicity; for example, 50,000 per second. A carbon transmitter is shown at *T*. The diaphragm of the transmitter is marked *P*. *A* is the sending antenna.

One of Professor Fessenden's claims is as follows:

" In a system of signaling by electromagnetic waves, the combination of means for the practically continuous generation of electromagnetic waves or impulses, means for modifying or changing the character of such waves or impulses without interruption of their continuity, and an indicating means or mechanism at the receiving station operative by the electromagnetic waves or impulses, substantially as set forth."

In carrying out the invention Professor Fessenden, in 1908, constructed a high-frequency alternator, with an output of 2.5 kilowatts at 225 volts, and with a frequency of 75,000 cycles per second. This is a frequency well above the limit of audibility, and in fact a frequency sufficiently high to give, when the generator is connected directly or inductively to an antenna in resonance

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[1] U. S. Patent, No. 706,747, applied for Sept. 28, 1901, divided July 22, 1902, issued August 12, 1902.

with it, a wave length suitable for wireless telephony, namely, $3 \times 10^8/75{,}000 = 4000$ meters. With this apparatus, Professor Fessenden reports that he has carried on telephonic communication between Brant Rock, Massachusetts, using an antenna 440 feet high, and New York, using an antenna 200 feet high. The distance between these two stations is about 200 miles. Recently Professor Fessenden also reports successful wireless telephonic communication between Brant Rock, Massachusetts, and Washington, D. C., a distance of about 600 miles.

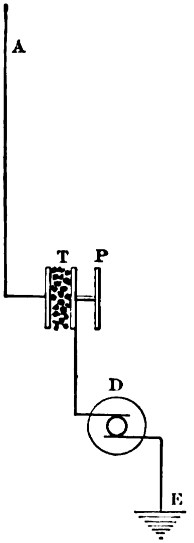

FIG. 219. Professor Fessenden's apparatus for wireless telephony, using high-frequency generator *D* and a microphone transmitter *T*.

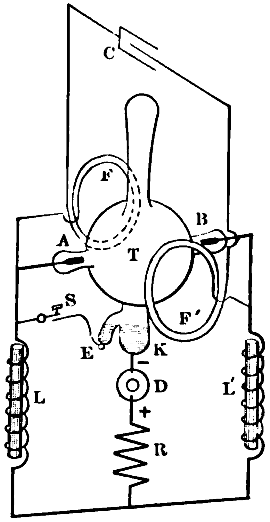

FIG. 220. Diagram of Vreeland's mercury-arc oscillator.

The Mercury-arc Method of Producing Sustained Oscillations. — In 1906 Mr. Frederick Vreeland[1] described a very interesting method of getting practically pure sinusoidal undamped oscillations from a direct-current supply. One form of Mr. Vreeland's apparatus is shown in Fig. 220. *T* is a glass vessel, exhausted to a high vacuum, and containing a mercury cathode *K* and two carbon anodes *A* and *B*. *E* is a small auxiliary electrode used in starting an arc in the chamber. The arc, when established, being fed from the direct-current source *D*, is divided into two branches

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[1] Physical Review, Vol. 27, p. 286, 1908.

— one between the anode A and the cathode K', the other between the anode B and the cathode K. A resistance R and two choke coils L and L' serve to steady and maintain the two arcs. Now an oscillation circuit consisting of a condenser C and two coils F and F' is connected between the two anodes A and B. The coils F and F' in the oscillation circuit serve as field coils to deflect the arc inside the vacuum bulb, and to cause the cathode stream of this arc to oscillate in a plane perpendicular to the axis of the coils in such a manner that this oscillating cathode stream impinges first on one and then on the other of the anodes A and B. The manner in which this deflection of the cathode beam is produced is as follows:

At the start, the current tends to divide equally between the two arcs in the bulb, but there are always some variable inequalities in the conductivities of the two paths. These irregular fluctuations are usually sufficient to start the oscillations, after which they give place to the periodic fluctuations controlled by the alternating field. The action of the magnetic field is such as to produce a deflection of the cathode beam, and when this beam is deflected, say from the anode B to the anode A, there is a tendency for the current to pass wholly or largely from the anode A to the cathode K, due to the fact that the path from B is interrupted or increased in resistance. As the choke coils L and L' oppose any change in the current passing through them, this results in the current in the branch L' flowing through the oscillating circuit $F'CF$ from right to left, thus traversing the field coils in such direction as to increase the deflection of the cathode beam toward the left, thereby augmenting still further the inequality of the two paths through the tube and increasing the current through the oscillating circuit. This continues until the condenser C charges to a certain point, when it begins to discharge, reversing the field, and causing the arc to be deflected in the other direction, so as to force the current through the oscillating circuit from A to B. This process, being repeated indefinitely, results in feeding the energy into the oscillating circuit in synchronism with the oscillations, which are thus maintained at constant amplitude and at a frequency determined by the self-inductance and capacity of the circuit. A photograph of the completed apparatus is shown in Fig. 221.

I am not able to say whether or not Mr. Vreeland has, up to the present, been able to get the frequency of his oscillation producer up to the pitch required for wireless telephony. His apparatus is, however, very ingenious and full of promise.

Method of Applying the Microphone to Modify the Oscillations. — Having described methods of producing sustained or persistent oscillations I wish next to show briefly diagrams of connections by which the carbon microphone may be applied to modify these oscillations in accordance with the vibrations of the voice. In most of these diagrams I have represented the source of the persistent oscillations as a singing arc, such as has been devised by Simon, Duddell, and Poulsen. It will easily be seen how these

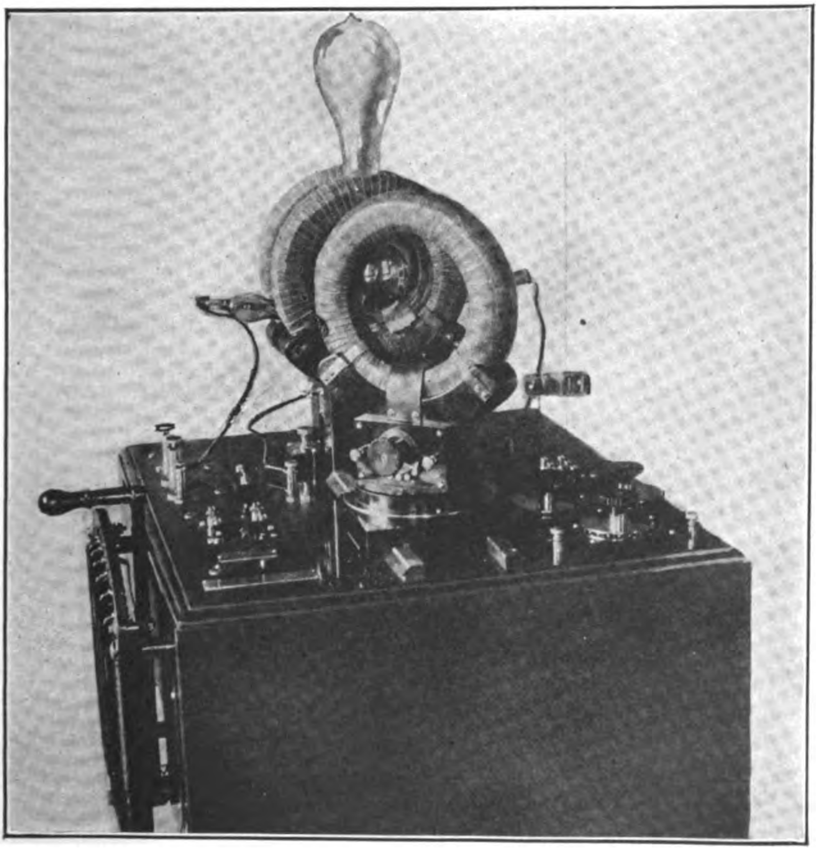

Fig. 221. View of Mr. Vreeland's apparatus.

diagrams should be modified to permit of the use of Fessenden's high-frequency generator or Vreeland's mercury-arc oscillator.

Figure 222 shows the microphone in series with the direct-current dynamo of the feeding system. To be used in this manner, the microphone must have high current-carrying capacity, and for this purpose some inventors have proposed to use several microphones in parallel, — all of the diaphragms facing upon a common air chamber into which the words are spoken.

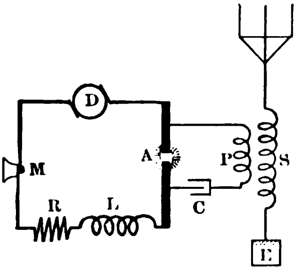

Fig. 222. One method of applying the microphone *M* to wireless telephone circuit.

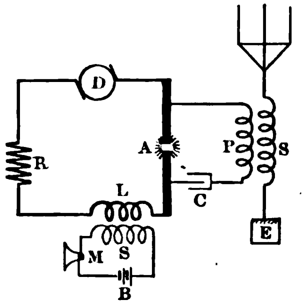

Fig. 223. Showing the microphone *M* in a circuit inductively coupled with the feeding circuit of an arc used in wireless telephony.

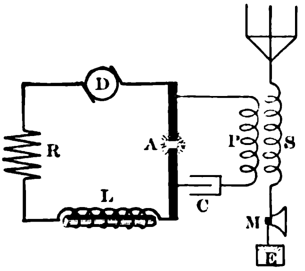

Fig. 224. Microphone *M* between secondary helix and ground.

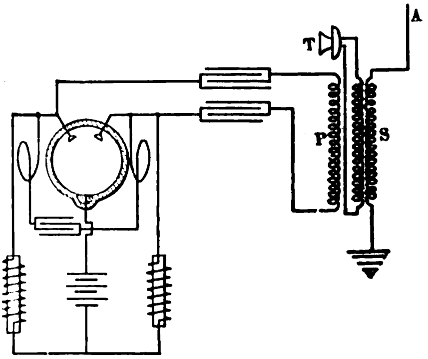

Fig. 225. Microphone *T* inductively coupled with secondary helix for wireless telephony.

Figure 223 shows the microphone transmitter connected in circuit with the primary of a transformer *S*, the secondary of which, *L*, is in series with the dynamo and the arc. In this case the heavy current of the arc does not go through the microphone. In common with the method of Fig. 222 there is the disadvantage that the microphonic modifications of current have to traverse the generator circuit, and hence meet with high impedance.

Figure 224 shows the microphone connected in series with the antenna circuit, between the secondary of the oscillation transformer *PS* and the ground connection.

Figure 225 shows a method proposed by Mr. Vreeland and others in which the microphone circuit is inductively connected with the secondary *S* of the oscillation transformer.

Other methods of connecting the microphonic transmitter to the oscillating circuit are also employed.

Practical Results in Wireless Telephony.—I have briefly pointed out in the preceding paragraphs the general processes employed in wireless telephony. The small amount of space here devoted to the subject is not to be taken as evidence that wireless telephony is a simple or unimportant branch of the science of electric-wave transmission of intelligence.

To be able to modulate a train of electric waves by waves of sound existent in the air between the mouth of the speaker and a transmitting diaphragm, and to be able to receive these modulated electric waves at a distance and reconvert them into sound waves, is a very remarkable achievement of scientific ingenuity, even when the sending and receiving stations are close together. Wireless telephony has, however, gone far beyond this stage; and Fessenden in America, Poulsen in Denmark, Majorano in Italy, and Messrs. Colin, Jeance and Mercier in France, have severally reported successful wireless telephonic transmission of speech to distances ranging from 40 to 600 miles. Even if these experiments have been lacking in some details of perfection, we cannot doubt that practical wireless telephony, especially between ships at sea at a considerable distance apart, is a possibility of the present time or of the immediate future.

CHAPTER XXVII

SOME DETAILS OF CONSTRUCTION OF WIRELESS TELEGRAPHIC APPARATUS

It is beyond the scope of an elementary treatise to enter extensively into a discussion of the engineering details of a wireless telegraph installation. In fact, much of the wireless telegraphic engineering of the present time is done by methods of construction and trial rather than by scientific prognosis. There are, however, certain elementary facts that may be of service to amateurs engaged in constructing or operating wireless telegraphic apparatus, and that at the same time may be not without interest for the general reader. Some of these elementary facts regarding construction are here presented.

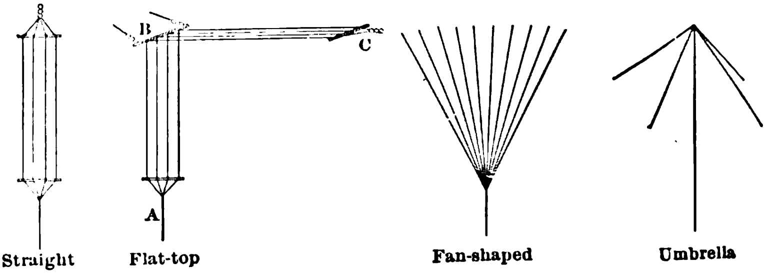

Fig. 226. Types of antenna.

Antenna. — The character of the equipment that may be employed in a given instance depends on the facilities that exist for the erection of an antenna. A few simple types of antenna are represented in the diagrams of Fig. 226.

The Flat-topped Antenna. — Of these types, the flat-topped antenna usually gives the best results for a small installation. The flat-topped antenna consists of the nearly vertical portion AB and the nearly horizontal portion BC. The horizontal portion does not contribute much as a useful radiating member, because waves emitted from this portion have their electric force parallel to the earth's surface, so that the part of this radiation that travels out along the surface of the earth induces currents in the earth and is rapidly absorbed. The remainder of the energy radiated from this horizontal portion travels prevalently upward and, save for contributing to the directiveness of transmission as has been pointed out in Chapter XXV, does not have much effect at the receiving station unless it is desired to transmit to a balloon, when this upward-traveling component is most useful.

The horizontal portion of the flat-topped antenna is, therefore, chiefly serviceable as a capacity at the top of the vertical part, which latter is the chief radiating member. As to the amount of the capacity it is interesting to note that a single wire 100 feet long and $\frac{1}{8}$ inch in diameter when alone in space has as much capacity as an isolated flat metallic disc 16 feet in diameter. (See formulas for calculation in Appendix II.) From this it will be seen that the horizontal top to the antenna is a far more economical elevated capacity than any kind of a metallic sheet such as was employed in Marconi's early experiments.

Comparison of Flat-topped with Straight Antenna. — In order to illustrate some of the principles involved, let us next compare the radiation from a single vertical wire 100 feet long and say $\frac{1}{8}$ inch in diameter with that from a flat-topped antenna consisting of a vertical wire 100 feet long having at the top a horizontal extension of the same length. For the purpose of this comparison we shall employ the experimental curve of current distribution found in Chapter XIV (Fig. 82). In the first place the flat-topped antenna, because of its greater length of wire, has approximately twice as much capacity as the simple vertical antenna. This means that if we charge the two antennæ to the same potential, about twice as much electricity will flow during one oscillation of the flat-topped antenna as during one oscillation of the simple vertical antenna; but the time of the oscillation in the former case will be about twice as long; therefore the maximum current flowing to the ground will be about the same in the two cases. Let us now plot the approximate current-distribution curves for the two cases, assuming the same current at the base; and in doing this we shall make the further assumption that the distribution in the bent antenna is approximately the same as it would be for a straight antenna of the same length. The curves obtained are given in Fig. 227. In these curves the value of the current at any point of the length of the antenna is plotted as a distance between the antenna and the curve. Careful plotting and measurement of these curves show that the average current in the vertical portion of the flat-topped antenna is .88 of the maximum current at the base; whereas the average current for the vertical antenna is only .62 of the current at the base. Dividing .88 by .62, we find that the average current in the vertical portion of the flat-topped antenna is 1.41 times the average for the simple vertical antenna. From these considerations it appears that we have gained 41% in effective current by the use of the flat-topped extension. We could gain approximately the same by extending the simple antenna about 41 feet upwards. From this we may conclude that two poles of 100 feet in height and 100 feet apart supporting a flat-topped antenna would give approximately the same service as a single pole 141 feet high supporting a single vertical antenna.

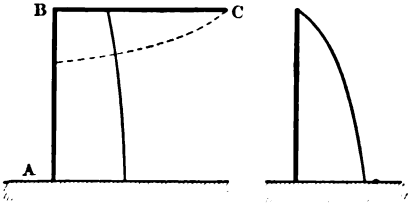

FIG. 227. Comparison of current distribution on a flat-topped antenna (left) with that on a straight antenna (right) of the same height.

On account of difference in damping and on account of the effects on radiation introduced by the difference in wave length in the two cases, and also on account of the directive emission from the flat-topped antenna, the problem is not so simple as is here represented; and the numerical deductions are indeed only very rough approximations, which serve merely to show wherein consists the efficacy of the flat-topped antenna; namely, in the increased average current in the vertical part due to the capacity of the horizontal part.

Antenna of Several Wires. — Instead of employing a single wire in the antenna, as in the illustrative example here given, several wires are usually employed. It should be noted, however, that *n* wires placed side by side have not anything like *n* times the capacity of a single wire; because the charge on one wire repels the charge on the other wires, and therefore the charge that the system will take under a given electromotive force applied at the base is not multiplied in the ratio that the number of wires is multiplied.

For an economical installation from four to six wires may well be employed in the antenna, and by the use of light bamboo spreaders they can easily be supported three feet or more apart.

Marconi Antenna at Clifden. — An example of the use of the flat-topped antenna on a large scale is afforded by the Marconi high-power station at Clifden, Ireland. The horizontal part of the antenna of this station consists of 200 wires 1000 feet long supported 180 feet above the earth The wave length is about 4000 meters.

The Umbrella Antenna. — When only one supporting pole is available, either the straight type or the umbrella type of antenna is usually employed. The umbrella type meets with frequent use in small amateur stations and in the portable stations employed by armies. In this type the aerial system consists of a vertical portion terminating above in a system of wires inclining downward. These inclining wires are usually the guy wires, while the vertical part may be either a wire leading to the top of the pole, or the pole may itself be of metal and serve as the vertical conductor. A diagram of an umbrella type of antenna with a metallic pole serving as the vertical conductor is shown in Fig. 228. The

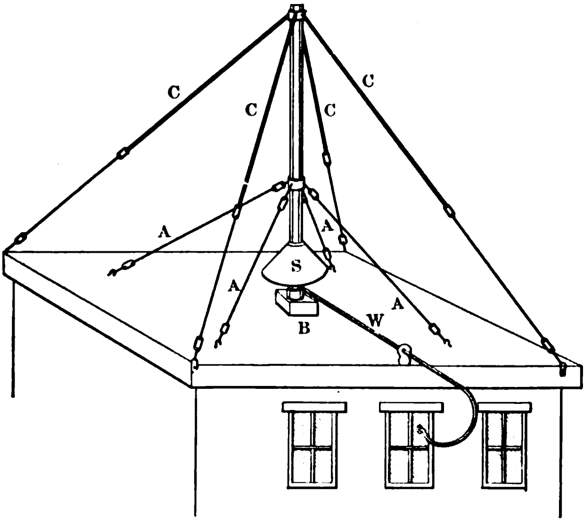

FIG. 228. Umbrella type of antenna.

metallic pole used in a small installation may be two or three sections of ordinary tinned gutter pipe or of one-inch iron water pipe. To keep such an antenna straight, a separate set of guy wires must be used for every section of pipe employed. The bottom of the metallic pole is supported on an insulating base *B*, which is protected from rain by a shelter *S* placed above it and connected to the pole. The wire *W* leading from the operating room is connected directly to the pole near its base. The lower guy wires *AAAA* are preferably insulated from the pole and from the housetop. The upper parts of the upper guys *CCCC* are connected to the top of the pole, and these serve as a capacity extension to the antenna. At a suitable distance from the top of the pole high-tension insulators are inserted so as to terminate the antenna.

With this form of antenna it will be observed that the oscillation in the vertical pole and that in the inclined extensions *CCCC* are partially opposite to each other, and therefore partially neutralize each other with respect to radiation. The length of the guy-wire extension that can thus be used with advantage will depend upon the number of the guys and their inclination.

The Fessenden Tower at Brant Rock. — A very striking example of a station making use of the supporting structure as antenna is the powerful station of the National Electric Signaling Company at Brant Rock, Massachusetts. For the antenna of this station there is provided a cylindrical steel tower 440 feet high, carefully insulated at the base and provided above with extension capacity in the form of four horizontal arms each 80 feet long. These arms being horizontal do not offer the disadvantage of partially neutralizing the radiation from the tower.

When it is remembered that this very tall and very heavy steel tube must be sufficiently insulated from the earth to withstand the enormous potential developed in a very high-power wireless telegraph sending station, it will be seen that the design and erection of such a plant, which was accomplished by Professor Fessenden, is a very considerable feat of mechanical and electrical engineering.

It is interesting to compare the capacity of this large tube with that of a small wire. With the aid of Formula VII of Appendix II, it can be shown by calculation that a tube 440 feet (13,510 cm.) high and 3 feet in diameter (46 cm. in radius) has a capacity, when alone in space, that is only about twice as great as the capacity of a wire the same length and $\frac{3}{8}$ of an inch (1 cm.) in diameter. Therefore, so far as concerns capacity, a few small wires five or six feet apart would be the equivalent of this large steel tube.

The Ground. — The theory of the action of the ground has been discussed in Chapter XIV. In practice, for a small station a satisfactory ground can be obtained by a connection to the pipes of a water supply. Where this is lacking, a good arrangement is to bury a netting or network of wires at a short depth below the surface of the earth. This may be supplemented by metallic pipes driven to considerable depths into the earth, and also by wire netting spread out on the surface of the earth. When the station is located near the sea or other body of water, the wire netting or wires provided with terminal plates may be led into the body of water. On board ship, the grounding is usually effected by a heavy wire attached to the metallic hull of the ship. In the high-power land stations, netting and wires are made to ramify the surface of the earth for many acres.

We have seen in Chapter XIV that a properly resonant artificial conductor supported without contact with the earth serves as a very good ground. The difficulty about the artificial ground is the fact that the artificial ground should be tuned along with the aerial system in order to get resonance with different wave lengths.

Sending Condensers for a Coupled Transmitting Station. — The details of construction of the simple Marconi apparatus of 1896 need not be given. When a sending station of the inductively coupled or direct coupled type is to be employed, the sending condensers must be electrically strong in order to permit the storage of the large quantities of electricity used in producing the waves. Among the types of condenser employed for this purpose the bank of Leyden jars or of flat glass plates provided with metallic coatings are most familiar. The use of tinfoil, for the coating of Leyden jars or flat-plate condensers for use in wireless telegraphy, has been largely discontinued. In the case of the flat-plate condensers copper or brass sheets between the plates in the place of the tinfoil that was formerly much used gives a much smaller loss of energy, and consequently much smaller heating of the condenser. Ordinary window glass, when selected free from flaws, is electrically stronger than plate glass for making glass-plate condensers. When high power is to be used, the flat-plate condensers should be submerged in castor oil to prevent brush discharge.

In the case of the Leyden jars, when used in stations of large power, glass of especially high electric breaking strength is employed and the tinfoil of other days is now usually replaced by a coating of silver or copper electrolytically deposited on the inner and outer surface of the jars. A photograph, lent me by Mr. Pickard, of some jars coated in this way by the Wireless Specialty Apparatus Company of New York, is shown in Fig. 229.

Air Condensers, formed of metallic plates with air between as dielectric, are said to be employed as sending condensers in Mr. Marconi's high-power stations at Poldhu, Clifden and Wellfleet.

Condensers employing compressed air as dielectric have been employed by Mr. Fessenden in his Brant Rock station and in some of the ship installations supplied by The National Electric Signaling Company to the United States Navy. The dielectric constant of the compressed air is about the same as that of air at atmospheric pressure. The purpose in compressing the air is to increase its disruptive strength so as to enable the condenser to stand higher potentials. The disruptive strength is approximately proportional to the gas pressure.

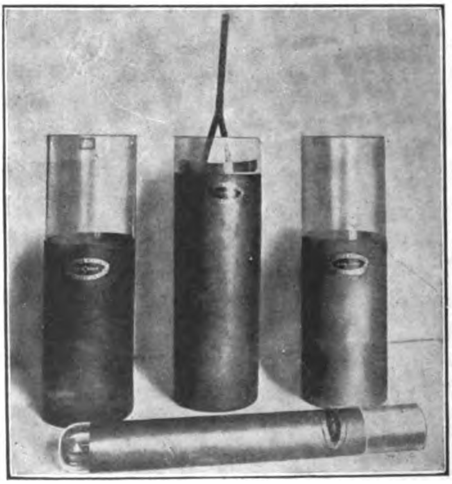

Fig. 229. Copper-plated Leyden jars.

Amount of Capacity to be Used at a Given Station. — The amount of capacity to be used at a given coupled-type of sending station depends upon, (1) the amount of power to be supplied to the condenser; (2) the number of sparks per second, and (3) the voltage at which the discharge occurs. As a specific example, let us suppose that the power is to be supplied by an alternating current source of n cycles per second. By means of a transformer with its primary connected to the source of power and its secondary attached to the condenser, we may step up the potential to the value required to produce the required spark. Let us suppose the transformer to supply P kilowatts of power to the condenser, and let us choose the condenser and the spark gap to be such that the condenser charges to a sparking potential only once during each half-cycle; that is, $2n$ times per second.

Now to charge a condenser *once* to a potential of V volts requires an amount of energy,

$$W = \tfrac{1}{2} QV \text{ joules}, \qquad (1)$$

where Q is the number of coulombs of electricity required and $\frac{1}{2}V$ is the average potential during the charge. (See Appendix I.)

And, from the definition of capacity,

$$Q = CV, \qquad (2)$$

where C is the capacity of the condenser in farads.

Substituting the value of Q from equation (2) in equation (1), we have

$$W = \tfrac{1}{2} CV^2 \text{ joules}, \qquad (3)$$

V being the potential in volts to which the condenser is charged.

In our supposed case the condenser is charged $2n$ times per second; therefore the energy expended per second, which is the power supplied, is

$$W = 2n \times \tfrac{1}{2} CV^2 = nCV^2 \text{ joules per second.} \qquad (4)$$

But 1 joule per second is 1 watt, and 1000 watts make a kilowatt; therefore if P is the power in kilowatts,

$$P = \frac{nCV^2}{1000} \text{ kilowatts.} \qquad (5)$$

In interpreting this formula, it must be remembered that V is the potential to which the condenser is charged at the time that the spark begins.

The formula (5) is very useful in practical computations. By a simple transposition of terms, equation (5) may be put in the form

$$C = \frac{1000 \times \text{Power in Kilowatts}}{nV^2}. \qquad (6)$$

From this we can calculate the capacity required in a given case, provided we know the power to be employed, the number of cycles, and the voltage to which the condenser is to be charged. For a given source of power we can employ either a large condenser charged to a low potential or a smaller capacity charged to a higher potential. A simple computation, which is not here given, shows that approximately the same volume of dielectric (e.g., glass) will have to be used in the condenser in either case.

In estimating the amount of capacity to be employed to consume a given amount of power, according to formula (6), it is well to estimate about 15,000 volts to the centimeter of spark length; for this is about the value of the potential when the spark gap is heated and ionized by continuous sending. On the other hand, in estimating the amount of dielectric to use for sufficient strength to stand the charge without breaking, it is well to estimate about 39,000 volts to the centimeter; for the voltage will rise to this value when the station is first started up.

The Charging Transformer. — After the dimensions and capacity of the condenser for the sending station have been settled upon, the transformer must be designed to be in resonance with the condenser. The proper proportioning of the primary and secondary inductance and the mutual inductance of the charging transformer of the sending station is one of the most troublesome factors arising in connection with wireless telegraphy design and construction, and cannot be adequately discussed in an elementary treatise. The fact to be kept in mind is that the transformer for this purpose must have entirely different properties from those possessed by an ordinary closed iron-core lighting transformer, because the lighting transformer is designed to supply more and more power as the load is made of lower and lower resistance; while with the wireless telegraph transformer the load is a condenser, which will attain a maximum charge for a certain *resonant relation* of the constants of the transformer to the capacity of the condenser. A spark will then pass. This spark amounts to a short-circuit of the secondary of the transformer. Under this condition an ordinary closed-core transformer would supply a maximum amount of power right across the short-circuited gap, so that this gap would sustain an arc, and the condenser would then not charge up again. This is not desired. What is desired is, that when the discharge of the condenser occurs and short-circuits the secondary of the transformer, the transformer should be so designed that it will draw a very small amount of power, and allow the spark to extinguish promptly after the discharge of the condenser.

A mathematical examination of this problem shows that this result can be obtained with a proper adjustable resistance placed in the primary circuit of the transformer, if a common closed-core transformer is used. The same result can be more economically obtained by the use of an adjustable inductance in series with the primary. It can also be attained by an adjustable inductance in series with the secondary of the closed-core transformer.

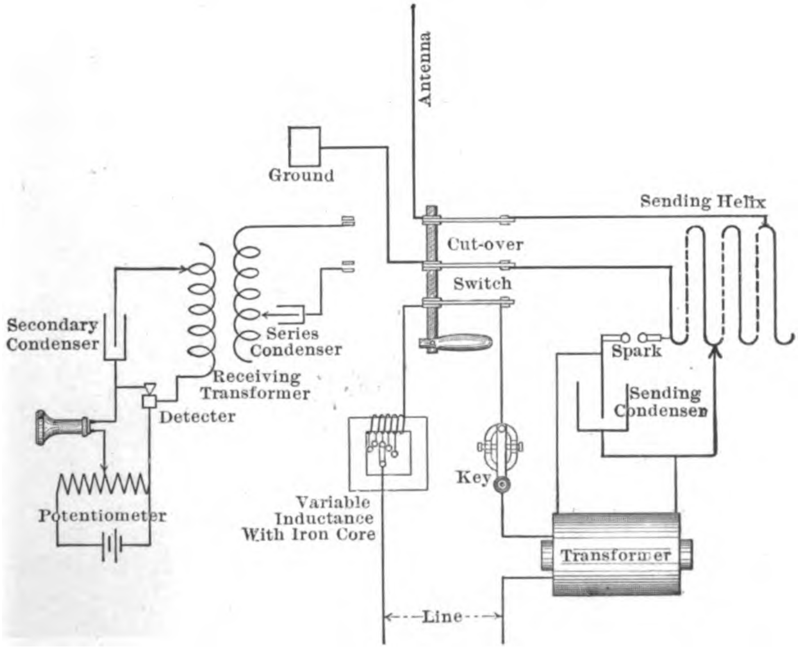

FIG. 230. Diagram of transmitting and receiving installation.

With an open-core type of transformer and an adjustable inductance in the primary circuit considerably greater flexibility in attaining resonance with condensers of different capacities is possible, and many engineers prefer the open-core transformer.

Sending Helix. — The construction of the sending helices of the direct-coupled and the inductively coupled type is shown in the photographs of Figs. 166 and 168 respectively.

Sending Key. — With power not exceeding 5 kilowatts at a voltage not higher than 150 volts, the primary circuit can be interrupted with an ordinary Morse telegraph key provided with heavy platinum or silver contacts. For larger values of the power some form of relay key by which the current is broken between large contacts under oil is generally employed.

Diagram of Sending and Receiving Circuit with Cut-over Switch. — In the diagram of Fig. 230, which shows the connections for a complete station, the sending apparatus is shown at the right, the receiving apparatus at the left and the cut-over switch for throwing from sending to receiving is shown near the center. This switch usually has three blades, mounted on a hard rubber axis, and sufficiently far apart to avoid sparking between the blades of the switch or from the sending to the receiving apparatus. The switch is shown in the position for sending; two of the blades join respectively the antenna and the ground to the sending helix, and the third blade closes the line circuit to the key and transformer. When the switch is thrown to the left, the antenna and

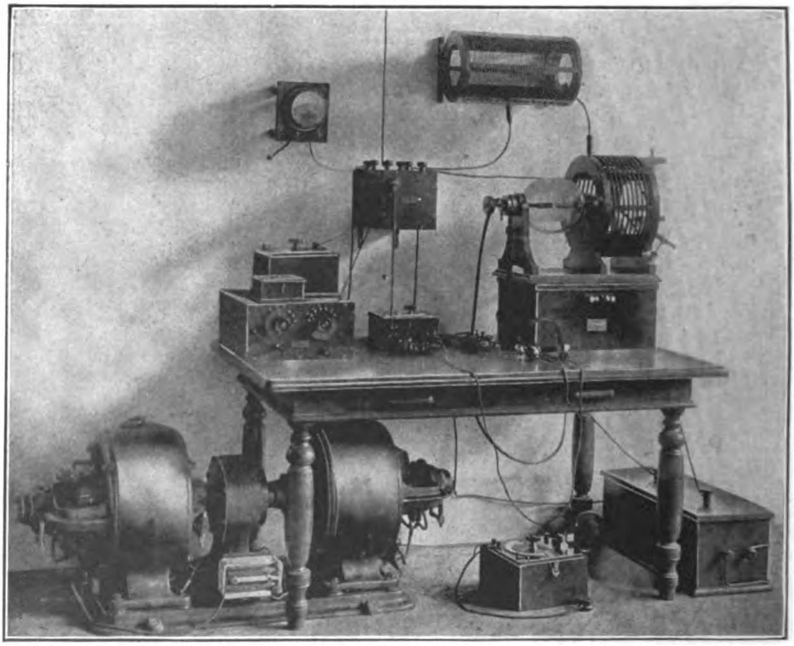

FIG. 231. View of installation.

ground are joined to the primary of the inductively connected receiving transformer, and the line circuit is opened so as to avoid a possible accidental discharge of the high-potential circuit while receiving.

A photograph of a station with approximately the arrangement of circuits here indicated is shown in Fig. 231.

I will next describe some of the parts of the receiving apparatus, and shall employ in the description the designations used in Fig. 230.

Receiving Condensers. — The series condenser, which is employed in the antenna circuit between the primary of the receiving transformer and the ground, should be an air condenser of the semicircular plate type, like that shown in the photograph of Fig. 81. The introduction of this condenser has the effect of shortening the wave length of the antenna, so as to adapt an antenna of long wave length to receive short waves. Tuning by means of this condenser gives a better discrimination of signals according to their wave lengths than can be obtained by the use of adjustments in the detector circuit; nevertheless this series condenser can often be dispensed with.

The secondary receiving condenser, in circuit with the detector, cannot be dispensed with. This condenser may also be of the semicircular air type, but its capacity should usually be larger than can be attained with a single condenser of this type. If the secondary of the receiving transformer is adjustable as to inductance, the secondary condenser does not require to be capable of fine adjustment, and a condenser with mica plates as dielectric, and provided with step-by-step adjustment, may be used. In fact, with adjustable inductances in the transformer, the value of the secondary condenser may well be entirely fixed.

Fig. 232. A receiving transformer.

Receiving Transformer. — A photograph of one type of receiving transformer is given in Fig. 232. The secondary coil of this transformer is shown near the top of the apparatus. The primary is the long solenoid of a single layer of wire wound on a cylindrical paper, glass, or vulcanite drum. The inductance of this primary coil can be varied by the sliding contact. After this adjustment has been made, the secondary may be moved as a whole down or up, so as to bring it into proper inductive relation to the primary.

The reader will easily see how this construction may be varied; for example, both the primary and the secondary coils may be wound on long glass tubes of different diameters. One of the coils may then be mounted inside of the other, and the inductance of both coils can then be varied by sliding contacts, — the contact to the inner coil being carried by a rod that protrudes through the head of the coils.

The Detector and Potentiometer. — The detector usually employed at the present time is either an electrolytic detector or a crystal-contact rectifier. Details in regard to these detectors have already been partially given. For the electrolytic detector, platinum wire from two to four ten-thousandths of an inch drawn so as to form the core of a larger wire of silver is usually employed for the most sensitive receiver of the electrolytic type. The electrolyte used is generally 20% nitric acid. The fine platinum wire must be capable of delicate adjustment up and down so as to bring it into minute contact with the electrolyte. In attaining this result the wire with the silver on it is attached to an arm movable by a micrometer screw. It is then dipped into the electrolyte to a depth of about $\frac{1}{16}$ of an inch, and a current somewhat stronger than the operating local current is sent through it from the fine point to the electrolyte so as to remove electrolytically the silver coating from the point. When this has been accomplished, the point is raised until it is in very minute contact with the liquid, the voltage in the local circuit through the detector and telephone is reduced until the hissing noise in the telephone made by the local current through the detector just ceases. The detector is then in delicate adjustment for receiving. The sensitiveness of the detector, and its readiness to receive signals, may further be tested by a buzzer device for that purpose.

The accurate adjustment of the local voltage is achieved by the use of a *potentiometer*, which is shown in the diagram of the complete station, Fig. 230. This potentiometer consists of a coil of resistance wire of about 500 ohms, connected to about three Leclanché cells or three dry cells. This resistance coil is wound on a tube and provided with a sliding contact. The adjustable voltage for the local circuit is taken from this resistance by two leads, one to the end of the resistance and the other to the sliding contact. The exterior of a potentiometer in which the resistance is wound on a circular collar and the sliding contact carried by a rotating arm is shown in Fig. 233.

FIG. 233. View of a potentiometer.

Two electrolytic detectors, mounted on a common base with this potentiometer, are shown in Fig. 234.

With some of the crystal-contact detectors a small voltage in the local circuit may be an advantage. The potentiometer in this case need, however, employ only one dry cell or one Leclanché cell.

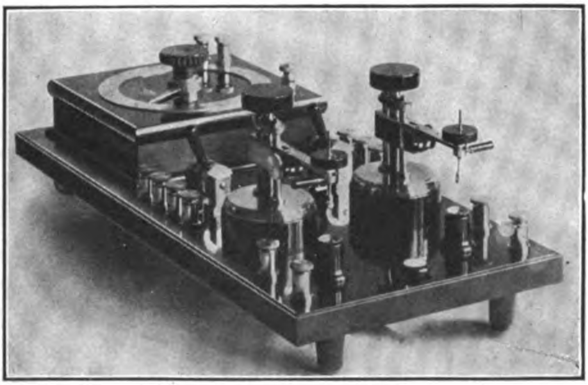

FIG. 234. Two electrolytic detectors with potentiometer.

Reliance on Principles Rather than on Details. — The details of construction here given appertain primarily to what is at the present time the most usual type of wireless telegraph station. Progress in this respect is, however, very rapid, and it is not at all unlikely that the reader who is engaged in the practical study of wireless telegraphy may readily see how to make improvements on any of the constructions here suggested.

In order to get the greatest interest and benefit out of practical experiments in any science, the reader is advised to seek carefully for the meaning of any novelty that arises in his experience and to attempt to interpret his results in terms of the general principles of the subject.

CHAPTER XXVIII

CONCLUSION

THERE are at present many thousand wireless telegraph stations in daily operation in the world. The map of Fig. 235 shows the location of some of the stations on the Atlantic Coast of North America. On this map only the stations of the United States Navy on the coasts of the United States, Cuba, Porto Rico and

FIG. 235. Map showing location on the coast of North America of wireless telegraph stations belonging to the United States and to Great Britain.

Panama, and the stations of the British Government in its North American provinces, are represented. For lack of room and information all of the commercial and amateur stations have been omitted. When it is remembered that of the stations on the map many are capable of being heard at night for a distance equal to half the length of the whole coast, an idea can be formed as to the earnestness with which electric-wave telegraphy has been seized upon as a method of communicating intelligence. By sending out daily time signals, weather reports and storm warnings, and by responding to calls for aid from ships in distress, these governmental equipments have been of inestimable service to mariners, and have already saved thousands of human lives.

The history of this development is a striking example of the manner in which the labors of scientists in fields of pure research apparently unrelated to commercial applications may result in discoveries of the utmost material importance. Maxwell in his search for a rational grasp of the undulatory theory of light and Hertz in his experimental effort to establish a relation between electromagnetic force and the dielectric polarization of insulators were unwittingly laying the foundation for radiotelegraphy, which is, in fact, after all only a single development from among a host of other consequences of perhaps even greater significance that have grown out of the remarkable discoveries of Maxwell and Hertz.

APPENDIX I

ELEMENTARY FACTS ABOUT ELECTRICITY AND DEFINITIONS OF UNITS

Two sets of electrical units, based directly on the centimeter, gram and second, are in use for the measurement of electrical quantities. These two systems are both called centimeter-gram-second units (abbreviated c.g.s. units).

One of these sets of c.g.s. units (called the *electrostatic units*) is obtained from the laws of attraction and repulsion between charged bodies.

The other set of c.g.s. units (called *electromagnetic units*) is obtained by a consideration of the laws of electromagnetism.

In addition to these two sets of c.g.s., or *absolute* units, there is also in international use a set of units of a size somewhat better adapted to practical measurements, which are designated the *practical units.*

In defining these several units, we shall make use of some of the fundamental principles of electricity, which are here reviewed.

ON ELECTROSTATIC ATTRACTION AND REPULSION

Measurement of Electrostatic Forces. — The force of attraction or repulsion between two electrified bodies may be measured directly. One method is to attach one of the bodies in an unelectrified state to one arm of a delicate balance, and counterbalance it with a weight suspended from the other arm of the balance. Another body may now be brought up under the first; both bodies may be electrified, and their attraction be measured by the counterbalancing weight that must be added to bring the system again into equilibrium. This is the method employed in Sir William Thomson's absolute electrometer.

Another method, which is more sensitive for measuring electric forces, makes use of the torsion balance, in which a light lever is suspended by a fine fiber so as to be free to rotate by twisting the fiber. One of the electrified bodies is attached to one arm of the lever and counterbalanced; the other electrified body is brought up near the first *in a horizontal plane,* so that the force of attraction or repulsion tends to twist the fiber. By determining the torsional rigidity of the fiber, and the amount of twist given it by the electric attraction, the force of the attraction may be determined. This method was employed by Coulomb in measuring the force of attraction or repulsion between electric charges.

On the Proof of the Law of Inverse Square of the Distance. — Coulomb, by the use of the torsion balance, proved that the attraction or repulsion of two given charges of electricity is inversely proportional to the square of the distance between the charges.

A very sensitive method of testing this law was devised by Cavendish, and is based on the result obtained by Faraday in his so-called "ice-pail experiment." Faraday's experiment showed that electricity at rest on a closed conducting body resides only on the outside surface of the body. Cavendish proved mathematically that the only law of repulsion between like electrical charges that will produce this distribution of electricity on a conductor is the law of repulsion inversely proportional to the square of the distance.

Attraction or Repulsion Proportional to the Product of the Charges. — With the aid of the torsion balance, Coulomb showed that, if the distance between two charged bodies be kept constant, and the two bodies be charged with quantities of electricity Q and Q', respectively (measured in arbitrary units), the force of attraction between the two bodies, if they have unlike signs, or the force of repulsion between them, if they have the same sign, is proportional to the product of the charges.

Combination of Quantity Law with Distance Law. — A combination of the two laws above enunciated gives

$$F \sim \frac{QQ'}{r^2},$$

in which F is the force of repulsion between the two charges. If the two charges have unlike signs, their product will be negative and the force becomes a negative force of repulsion; that is, a force of attraction.

ELECTROSTATIC UNIT OF QUANTITY AND OF CURRENT

The C.G.S. Electrostatic Unit of Quantity. — The law of repulsion of electrical charges, stated in the preceding paragraph, suggests *a rational unit* in which to measure quantity of electricity.

The law is that the repulsion is proportional to the product of the two quantities divided by the square of the distance between them. The rational unit is chosen to make the attraction not only proportional to, but equal to, the product of the charges divided by the square of the distance (if the charges are in vacuo); that is, in rational units, in vacuo,

$$F = \frac{QQ'}{r^2}.$$

That this may be true F must be 1 when Q, Q' and r are all made equal to 1, as may be seen by substitution of the value 1 for Q, Q' and r. This leads to the following definition:

Definition. The c.g.s. Electrostatic Unit of Quantity is that quantity of electricity which, when placed at a distance of one centimeter, in vacuo, from an equal quantity of electricity, repels it with a force of one dyne.[1]

The c.g.s. Electrostatic Unit of Current is that current that delivers one electrostatic unit quantity of electricity per second.

ELECTROMAGNETIC UNIT OF CURRENT AND OF QUANTITY

By the use of the torsion balance and by reasoning similar to that employed in the experiments on electrostatics described above, it has been shown that two like magnetic poles repel each other with a force proportional to the product of the strengths of the poles and inversely proportional to the square of their distance apart. This leads to the following definition of a unit magnetic pole.

A Unit Magnetic Pole is that pole that, placed at a distance of one centimeter from an equal pole (in vacuo), repels it with a force of one dyne.

Now it has been shown in Chapter III that if a suspended magnet is placed parallel to a conductor of electricity and a current is sent through the conductor, one pole of the magnet is driven one way and the other pole of the magnet is driven in the opposite way, so that the magnet tends to set itself at right angles to the conductor.

By measuring the force exerted by the current on the magnet, the laws according to which the force acts in this case have also been discovered, and these laws have led to the selection of a set of units called the electromagnetic units.

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[1] In a medium of dielectric constant k the repulsion between two like charges is, $F = \frac{QQ'}{kr^2}$, where Q and Q' are in c.g.s. electrostatic units, r in cm., and F in dynes.

The force acting between the electric current and a magnetic pole depends on the strength of the current, the strength and position of the magnetic pole, and the shape of the electric circuit. In defining the electromagnetic unit of current, the form of the circuit selected is the circle of unit radius, and the pole used is the unit magnetic pole.

Definition. The c.g.s. Electromagnetic Unit of Current is that current that, flowing in a circle of one centimeter radius, exerts on a unit magnetic pole placed at the center of the circle a force of one dyne for each centimeter of arc of the circle.

The c.g.s. Electromagnetic Unit of Quantity is that quantity of electricity delivered in one second by an Electromagnetic Unit of Current.

Relation of the Electromagnetic Unit to the Electrostatic Unit of Quantity. — Experimental determinations of the ratio of the two c.g.s. units of electrical quantity have shown that

$$\frac{\text{The Electromagnetic Unit of Quantity}}{\text{The Electrostatic Unit of Quantity}} = 3 \times 10^{10} = v.$$

This is the velocity of light in centimeters per second. The fact that the ratio of these two units is equal to the velocity of light was also derived theoretically by Maxwell from his electromagnetic theory of light.

Ratio of the Absolute Units of Current. — From the fact that the unit of current is a unit quantity of electricity per second, it follows that

$$\frac{\text{The Electromagnetic Unit of Current}}{\text{The Electrostatic Unit of Current}} = 3 \times 10^{10} = v.$$

ON ELECTRICAL WORK, AND THE C.G.S. UNITS OF POTENTIAL

Having defined the units of current and quantity in both systems of c.g.s. units, we shall next proceed to a consideration of electrical work and potential.

Work and Potential Energy. — When a body is moved against a force tending to prevent the motion, work is done. The amount of work done is defined as the product of the force overcome by the effective displacement of the point of application of the force, the effective displacement being that component of the displacement which is parallel to the force. As an illustration, let us take the case of the force of gravitation due to the attraction of the earth for a body near the surface of the earth. This force is perpendicular to the surface of the earth. If now the body, which is attracted with a force F, is raised a vertical height h, the work done is $F \times h$; and this work is the same whether the body is raised straight up a height h, or whether it goes up a staircase or along an inclined plane or along any other line, provided its final position is somewhere in a horizontal plane at a distance h above a horizontal plane through its initial position. In carrying a body upward against the vertical force of attraction F from one horizontal plane to another at a distance h apart, the amount of work $F \times h$ is done. If the body is allowed to descend again, the body can do the same amount of work against any other force conveniently arranged; so the body is said to have *potential energy;* that is, the capacity to do work by virtue of its position. The body has more potential energy in the higher position by the amount $F \times h$.

Electrical Work and Electrical Potential. — Similar ideas are made use of in the study of electricity. These ideas, like those of the gravitational problem, are obtained from experience. Suppose we have a body E charged with positive electricity, and suppose a second body E', also charged positively, to be moved up toward the first against the force of repulsion between the bodies. Work is done, and as a consequence of the law of repulsion between the charged bodies, it can be shown by a theoretical method not given here that the work done in carrying a given charge from B to A is independent of the path.

The work done in carrying a *unit* quantity of electricity from B to A is called the difference of potential between A and B.

A point at an infinite distance from a system of charged bodies has a potential zero, and the potential at any point P is the work done in bringing a unit quantity of electricity from an infinite distance up to the point P.

Consistent with these principles we have the two following c.g.s. units for measuring potential and difference of potential.

The c.g.s. Electrostatic Unit of Potential. — Two points have a Difference of Potential of one Electrostatic Unit of Potential when the work done in carrying an Electrostatic Unit Quantity of Electricity from one point to the other is the c.g.s. unit of work (one erg).

The c.g.s. Electromagnetic Unit of Potential. — The two points have a Difference of Potential of one Electromagnetic Unit of Potential when the work done in carrying the Electromagnetic Unit Quantity of Electricity from one point to the other is one erg.

Method of Computing Electrical Work. — According to the definitions and principles given above, the work W done in moving Q units of electricity from one point to another, of which the average difference of potential during the transfer is V, is

$$W = QV,$$

in which W is measured in ergs, and Q and V are either both in Electrostatic or both in Electromagnetic units.

Ratio of the Units of Potential. —

$$\frac{\text{The Electromagnetic Unit of Potential}}{\text{The Electrostatic Unit of Potential}} = \frac{1}{v} = \frac{1}{3 \times 10^{10}}.$$

This relation follows from the ratio of the units of quantity given on page 332, together with the fact that the product of quantity by potential (work in ergs) must give the same result in both sets of units.

Another Aspect of Potential, Relating Potential Gradient to Electric Force. — The exact definition of potential given above is based on the idea of work. We may slightly change the aspect of this definition and obtain from it the fact that the potential of a point represents, in a way, the tendency of electricity to flow from the point, and that the difference of potential between two given points measures, in a way, the tendency of electricity to flow from the point of higher potential to the point of lower potential. Let us illustrate this, and obtain a more exact statement.

If two points have the same potential, no work is done in carrying a unit charge from one to the other; therefore, since work is force times effective distance, there is no electric force acting from one point to the other, and no tendency of a charge to move from one point to the other.

On the other hand, if *two fixed points* have a difference of potential, work is done in carrying the charge from one of the points to the other; there is, therefore, a force acting and tending to send a charge from the point of high potential to that of low potential; and the greater the difference of potential, the greater the work of carrying a unit charge the *same distance*, and therefore the greater the force acting from the point of high potential to that of low potential. It thus looks as if potential difference were proportional to, if not synonymous with, electric force.

However, another example will show how this idea needs to be slightly modified in order to give the exact relation of potential difference to electric force. Let us suppose that two points A and B have a certain difference of potential, and that two other points A' and B' *farther apart than A and B* have the same difference of potential as A and B; the work done in carrying a unit charge from A' to B' is the same as that done in carrying a unit charge from A to B (since potential difference is the same); but since the work is force times distance, and the latter distance is the smaller, the corresponding electric force will be greater. An examination of this proposition shows that the force acting on a unit charge in either case is proportional to the *fall of potential per unit length.*

This latter quantity is called *potential gradient,* and we have the result that the *force driving any given charge in a given direction is proportional to the potential gradient in that direction.*

This is true whether we are concerned with electric forces tending to send a current through the conductor or tending to move charged bodies as a whole. The electromotive force of a circuit, which is the work done in carrying a unit quantity of electricity completely around the circuit, is measured in terms of the same units as potential and difference of potential.

UNITS OF RESISTANCE, INDUCTANCE AND CAPACITY

Resistance. — In accordance with Ohm's Law (*current in a steady state equals electromotive force divided by resistance*),

The Unit of Resistance is defined as that resistance through which a unit electromotive force constantly applied will produce a unit current.

Inductance. — In accordance with the definitions of mutual inductance and self-inductance given in Chapter III, the unit in which each of these quantities is measured is defined as follows:

The Unit of Inductance is an inductance in which a unit electromotive force is generated by a current changing at the rate of one unit current per second.

Capacity. — Finally, from the definition of capacity,

The Unit of Capacity is the capacity of a condenser that is charged to a unit difference of potential by a unit quantity of electricity.

Either one of these definitions is true in any set of units provided each of the three magnitudes in a given definition is in the same set of units.

PRACTICAL UNITS

The following table contains the practical units, together with their equivalents in terms of the two sets of c.g.s. units:

Unit of	Practical Unit.	C.G.S. Units.	
		Electro-magnetic.	Electrostatic.
Quantity.....	1 Coulomb =	$10^{-1} =$	$10^{-1} \times v = 3 \times 10^{9}$
Current......	1 Ampere =	$10^{-1} =$	$10^{-1} \times v = 3 \times 10^{9}$
Potential.....	1 Volt =	$10^{8} =$	$10^{8} \div v = \frac{1}{3} \times 10^{-2}$
Resistance ...	1 Ohm =	$10^{9} =$	$10^{9} \div v^{2} = \frac{1}{9} \times 10^{-11}$
Capacity.....	1 Farad =	$10^{-9} =$	$10^{-9} \times v^{2} = 9 \times 10^{11}$
Inductance ..	1 Henry =	$10^{9} =$	$10^{9} \div v^{2} = \frac{1}{9} \times 10^{-11}$

APPENDIX II

CONCERNING THE CALCULATION OF RESISTANCE, SELF-INDUCTANCE AND CAPACITY

Formulas for High-frequency Electric Resistance. — The resistance of a circuit to the passage of a high-frequency electric current through it is greater than its resistance to a steady current. This is due to the fact that the high-frequency current, instead of distributing itself uniformly throughout the conductor, tends to concentrate in the outer layers of the conductor. In a qualitative way, the following considerations will explain the tendency of rapidly varying current to flow on the outside surface of the conductor. Let us take the case of a straight cylindrical wire, and let us suppose that there is at first a steady current flowing with a uniform distribution throughout the conductor. Let us now suppose a rapid variation to be made in the current; this variation will reproduce a variation in the magnetic field, and consequently will call into play an electromotive force tending to prevent the change of current. This induced electromotive force will not be the same throughout the whole cross section of the conductor, but will be greatest near the center of the wire, because the center of the wire is on the average nearer to every part of the cross section of the wire than is any other point within the wire. We have thus, during any periodic variation of a current in a cylindrical wire, a greater back electromotive force near the center of the wire, and consequently less current will flow in the central portion of the wire than near the surface. Such a distribution of current, which utilizes only partly the carrying facility of the wire, experiences a higher resistance than does a current uniformly distributed throughout the entire cross section of the wire.

Lord Rayleigh has derived the following formula for the *resistance of a straight cylindrical wire carrying an alternating current of high frequency:*

$$\frac{R'}{R} = 1 + \frac{k^2}{48} - \frac{k^4}{2880} +, \text{etc.}, \qquad (A)$$

in which R' = the resistance for the high-frequency current,
R = the resistance of the wire for a steady current,
k = an abbreviation for $\frac{\pi^2 d^2 n \mu}{\rho}$,
d = the diameter of the wire in centimeters,
n = the number of complete oscillations per second,
ρ = the specific resistance of the material of the wire in terms of absolute c.g.s. electromagnetic units,
π = 3.1416. . . , and
μ = the magnetic permeability of the material of the wire, and is unity for nonmagnetic wires.

The formula (A) is convenient for computation when k is less than 1. *When k is greater than 5 or 6, the following formula, also derived by Lord Rayleigh, is more accurate and convenient for calculation:*

$$\frac{R'}{R} = \tfrac{1}{2}\sqrt{k}. \qquad (B)$$

The succeeding table contains some computed values of resistance R' for 1,000,000 oscillations per second in terms of R, for different diameters of copper and German-silver wire.

TABLE FOR RATIO OF $\frac{R'}{R}$.

R' = Resistance for 1,000,000 oscillations per second,
R = Steady-current resistance.

Diameter in Cm.	Copper ρ = 1600.	German Silver ρ = 20,900.
.01	1.008	1.000
.02	1.117	1.000
.03	1.32	1.000
.05	1.95	1.000
.1	3.88	1.005
.2	7.85	1.09
.3	11.8	....
.4	15.7	4.30
.5	19.7	5.38
.6	23.6	6.5
.7	27.5	7.5
.8	31.	8.6
.9	35.	9.7
1.0	39.	10.7
1.5	59.	16.
2.0	79.	21.5

By reference to this table it will be seen that the resistance of a copper wire 2 centimeters in diameter is 79 times as great with the rapidly oscillating current as it is with a steady current. With decrease in the diameter of the wire the effect of the high frequency in diminishing the resistance decreases, and with a wire of copper 1 millimeter in diameter the resistance for current making one million oscillations per second is only 3.88 times as great as the resistance for steady current. For diameters below one-tenth of a millimeter, the high-frequency resistance of copper does not differ from the steady-current resistance. For radii greater than .5 millimeter the resistance of a circular copper wire is very nearly inversely proportional to the radius of the wire, while the steady resistance is inversely proportional to the square of the radius.

If we pass now from the case of copper to that of German silver, which has a specific resistance about 14 times as great as copper, it is seen that the departure between high-frequency resistance and steady-current resistance is not so great as for copper. For German-silver wires less than 1 millimeter in diameter the high-frequency resistance differs by not more than ½ of 1% from the steady resistance. Above one millimeter in diameter the ratio of R' to R for German silver increases progressively with increase of diameter.

The formulas here given apply only to approximately straight conductors, and should not be used to apply to wires wound into coils.

Formulas for Calculation of Capacity. — The following formulas serve for the calculation of capacity in some simple cases. The linear dimensions are to be measured in centimeters and k is the dielectric constant of the dielectric between the plates. The dielectric constant of air or other gas at ordinary atmospheric pressure is approximately 1. Approximate values of k for some other dielectrics are given in the table on page 341.

I. Capacity of a condenser of two parallel flat plates oppositely charged.

$$C = \frac{kA}{4\pi d} \text{ c.g.s. electrostatic units,}$$

in which A is the area of one of the plates overlapped by the other plate, d is the distance of the plates apart in centimeters.

This formula holds accurately only when the distance apart of the plates is small in comparison with the length and breadth of the plates.

II. Capacity of two concentric cylinders oppositely charged.

$$C = \frac{kl}{2\log_e \frac{R_2}{R_1}} \text{ c.g.s. electrostatic units,}$$

in which l = the overlapping length of the cylinders,
R_2 = the radius of the outer cylinder,
R_1 = the radius of the inner cylinder.

III. Capacity of a length l of two practically infinite parallel wires of the same radius, — the wires being oppositely charged.

$$C = \frac{kl}{4\log_e \frac{d}{R}} \text{ c.g.s. electrostatic units,}$$

d = distance apart of the wires,
R = radius of either wire in centimeters.

IV. Capacity of two concentric spheres, oppositely charged.

$$C = \frac{R_1 R_2}{d} \text{ c.g.s. electrostatic units,}$$

in which R_2 = the radius of the outer sphere,
R_1 = the radius of the inner sphere,
$d = R_2 - R_1$.

V. Capacity of a single sphere alone in space.

$$C = R \text{ c.g.s. electrostatic units,}$$

in which R = radius of the sphere.

VI. Capacity of a circular disc, or thin plate.

$$C = \frac{2R}{\pi} \text{ c.g.s. electrostatic units,}$$

in which R = the radius of the disc.

VII. Capacity of a single cylindrical wire alone in space.

$$C = \frac{l}{2\log_e \frac{l}{R}} \text{ c.g.s. electrostatic units,}$$

in which l = the length of the wire in centimeters,
R = its radius.

Rule for Several Condensers in Parallel. — If several condensers of capacities C_1, C_2, C_3, . . . are connected in parallel, the combined capacity C is

$$C = C_1 + C_2 + C_3 + \dots$$

Rule for Several Condensers connected in Series. —

$$\frac{1}{C}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\ldots$$

TABLE OF DIELECTRIC CONSTANTS

Substance.	Dielectric Constants.
Empty space.......	1
Air or other gas under atmospheric pressure..........	1 approx.
Glass	6 to 10
Mica...............	6.6
Hard Rubber	2.7
Kerosene Oil.......	2.0
Castor Oil	4.78
Water	80.

Formulas for Calculating Inductance. — The lengths are to be measured in centimeters, and the results are in c.g.s. electromagnetic units. The medium surrounding the conductors is supposed to be nonmagnetic.

I. The mutual inductance between a long single-layer solenoid and a lumped secondary wound about it.

$$M = 4\pi n_1 N_2 A \quad \text{c.g.s. electromagnetic units,}$$

in which

n_1 = the number of turns per cm. length on primary coil,
N_2 = the total number of turns on secondary coil,
A = the area of cross section included within the primary coil.

II. Self-inductance of a single-layer solenoid.

$$L = 4\pi^2 n^2 \left\{ \frac{2a^4 + a^2 l^2}{\sqrt{4a^2 + l^2}} - \frac{8a^3}{3\pi} \right\} \quad \text{c.g.s., electromagnetic units,}$$

in which

a = the mean radius of the solenoid,
n = the number of turns per cm. of length,
l = the length in centimeters.

This is accurate to better than ½ of 1% when l is not less than $4a$.[1]

III. Self-inductance of a length l of two practically infinite parallel wires in which the current is flowing in opposite directions (i.e., a return circuit).

$$L = 4l \cdot \log_e \frac{d}{R} \quad \text{c.g.s. electromagnetic units,}$$

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[1] Cohen, Bulletin of the Bureau of Standards, Vol. 4, p. 385, 1907–08.

in which d = the distance between centers of the two wires,
R = the radius of each wire, supposed equal,
l = the length of the pair of wires.

This formula assumes that the current is flowing only on the outside surfaces of the two wires, as is the case with oscillations of high frequency. (See next formula.)

IV. Self-inductance of a return circuit like that of III, with, however, a uniform distribution of current throughout the wires instead of merely on the surfaces.

$$L = 4l \left\{ \log_e \frac{d}{R} + \frac{\mu}{4} \right\} \text{ c.g.s. electromagnetic units,}$$

in which l = the length of the pair of wires,
d = the distance between centers of the two wires,
R = the radius of the wires, supposed equal,
μ = the magnetic permeability of the material of the wires, — the permeability of the medium between the wires being assumed unity (i.e., nonmagnetic).

V. Self-inductance of a length l of two concentric tubes.

$$L = 2l \log_e \frac{R_2}{R_1} \text{ c.g.s. electromagnetic units,}$$

in which R_2 = the inner radius of the outer tube,
R_1 = the outer radius of the inner tube.

In this case the distribution of current is supposed to be only on the adjacent surfaces of the tubes.

VI. Self-inductance of a single wire of length l.

$$L = 2l \left\{ \log_e \frac{2l}{R} - 1 \right\} \text{ c.g.s. electromagnetic units,}$$

in which l = the length of the wire,
R = its radius.

In this case the wire is supposed to be of small diameter in comparison with its length.

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