PRACTICAL ANALYSIS
OF
ULTRA HIGH FREQUENCY

Transmission Lines
Resonant Sections
Resonant Cavities
Wave Guides

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PREFACE

This booklet was prepared as an aid to the many members of our country's Armed Forces who are being trained, or who are engaged in the installation, operation and maintenance of Ultra High Frequency Radio-Electronic Equipment. It is hoped that this booklet will also benefit others who are concerned with the design and production of this type of equipment "behind the lines."

Every effort has been made to explain the theories involved in the simplest manner without the use of mathematics. The contents have been limited to subjects of current importance and on which the authors believe there is immediate need for practical interpretations.

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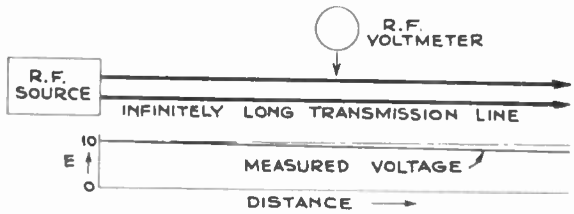
Transmission Lines

A transmission line is a means of transferring r-f energy from a source to a load in an efficient manner.

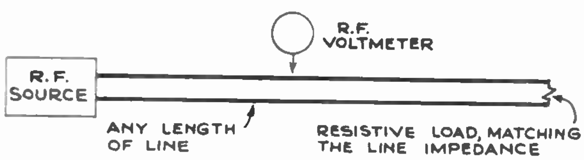
For simplicity, most of the illustrations in this booklet show parallel-wire transmission lines, but the information also applies to coaxial lines. The similarity between a section of parallel-wire line and a coaxial section may be seen by rotating a parallel-wire section about one wire so the outer arm forms a cylinder as shown.

The r-f voltmeter, referred to in the text, usually consists of an r-f rectifier and meter which indicates the rectified peak amplitude of the r-f voltage at any point along the line.

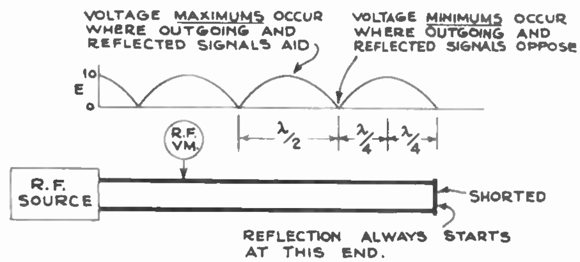
Standing Waves on Lines



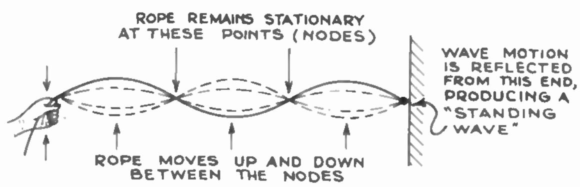
In this illustration, an r-f source is feeding r-f energy into a transmission line. If the line is infinitely long, the signal never reaches the end, and therefore cannot be reflected, so there are no "standing waves." The r-f voltage measured along the line gradually decreases due to losses in the line.



If the line is *terminated* in a resistive load that matches the line impedance (also termed "surge" or "characteristic" impedance), the outgoing signal is completely absorbed by the load. As a result, there are no reflections and no standing waves, and the voltage is essentially the same at all points along the line.



If the load is not resistive and matched to the line impedance, it reflects signal back into the line. *The combination of the outgoing and reflected signal produces a standing wave on the line.*



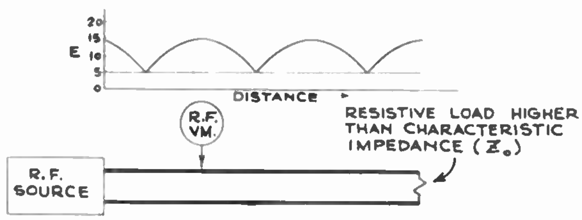
This analogy shows standing waves produced by wave motion and reflection on a rope. A similar analogy can be made to standing waves of sound along a pipe.

Standing Wave Ratio

$$\text{The standing-wave ratio} = \frac{\text{Minimum Voltage}}{\text{Maximum Voltage}}$$

This ratio indicates the ratio of mismatch of the load impedance.

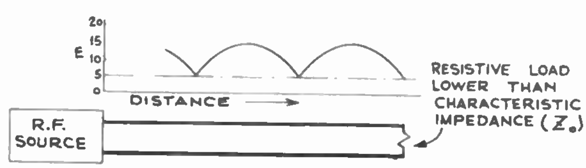
In the example shown below, the voltage at minimum's is 5, and the voltage at maximum's is 15.



The ratio is $\frac{5}{15}$ or 1 to 3.

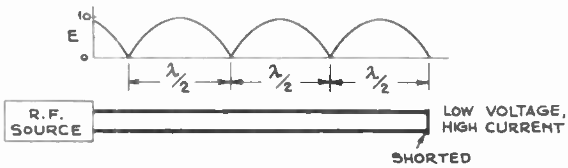
Hence, the load impedance is either 3 times larger than the line impedance, or one-third of the line impedance. (In the foregoing example, the voltage at the load is maximum, so the load impedance is higher than the line impedance.)

If the load has an appreciable reactive component the standing-wave ratio is only a rough indication of the impedance mismatch. This can be seen from the curves in the appendix.

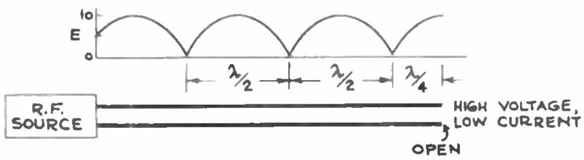


In the example shown above, the voltage at the load is minimum, so the load impedance is lower than the line impedance.

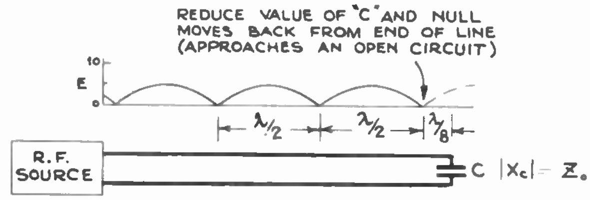
Position of Voltage Minimums and Maximums

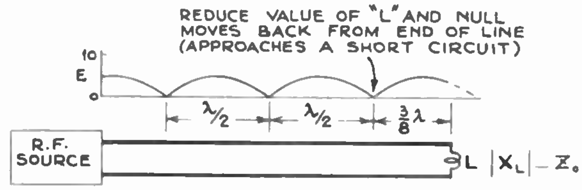


If the end of the line is shorted, the voltage at the short is low and the current is high. The first voltage minimum occurs a half-wave back from the end of the line.



If the end of the line is open, the voltage at the end is high, and the current is low. The first voltage minimum occurs a quarter-wave back from the end of the line.





For loads containing reactance, the standing-wave will be shifted, depending on the nature of the load.

Often it is desirable to speak of electrical degrees rather than fractions of a wave-length:

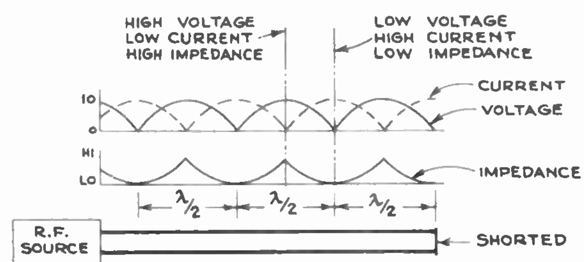
$\frac{1}{8}\lambda = 45°$	$\frac{1}{2}\lambda = 180°$	$\frac{7}{8}\lambda = 315°$
$\frac{1}{4}\lambda = 90°$	$\frac{5}{8}\lambda = 225°$	$\lambda = 360°$
$\frac{3}{8}\lambda = 135°$	$\frac{3}{4}\lambda = 270°$	

Impedance at Different Points Along the Line

The impedance at any point along the line is determined by the ratio of voltage to current at that point: If the voltage is high, the current at the same point is low, and therefore the impedance at that point is high.

If the line has low losses, and no energy is absorbed by the termination, the low-impedance points are equivalent to short-circuits, and the high-impedance points are equivalent to open circuits. If there is energy loss in the line or termination, the impedance tends to become more uniform along the line. *When the load matches the line, the impedance becomes uniform along the line, and is equal to the "characteristic" impedance.*

It should be noted that an open circuit, a short-circuit or a pure reactance at the end of the line will not absorb power. Standing-waves will therefore exist with such loads.



$$Z = \frac{E}{I}$$

Summary—Effect of Line Termination

(1) If a line *of any length* is correctly terminated with a resistive load that matches the line impedance, there are no reflections, and no standing-waves.

(2) If a line is not correctly terminated, the signal is reflected back from the load and this results in standing-waves.

(3) The value and nature of the load determines the *ratio* of voltage at maximum and minimum points along the line, and also the *position* of these maximum and minimum points.

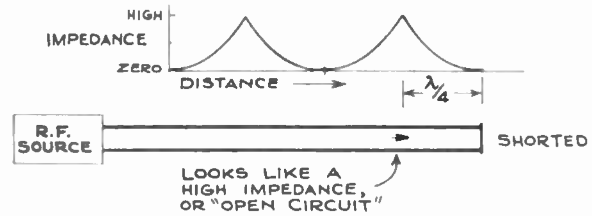
In most applications where a line is used to connect a signal source to a load (for instance, to connect a transmitter to an antenna) it is generally desirable to make the load match the line. *If the load is not matched, the length of the line becomes critical,* and incorrect length may affect the power output and frequency of the source. *When the load is matched to the line, the length of the line is not critical.* ("Matching" means that the load must be resistive and equal to the line impedance.)

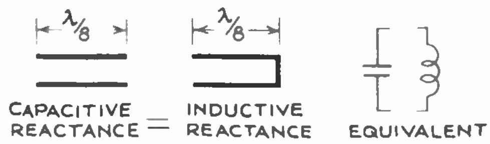
Resonant Sections

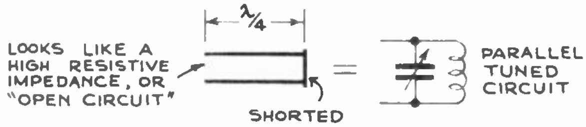
Quarter-wave and half-wave sections and their action as tuned circuits will now be considered. This action will be explained on the basis of change in impedance produced by standing waves along an opened or shorted line.

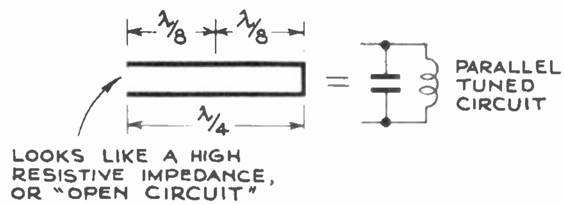
When sections of line are used as tuned circuits, their action depends on the existence of reflections and standing-waves to produce the effect of high-impedance and low-impedance tuned circuits. Therefore, sections of lines, when used as tuned circuits or transformers are either effectively shorted or opened at the end to produce the maximum standing-wave ratio and the highest or lowest possible input impedance, as desired in the application.

Quarter-Wave Shorted Section



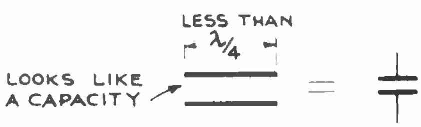




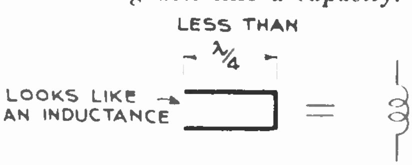


The quarter-wave shorted section at the end of the line looks like a high-impedance to the input signal, and being tuned, it is resistive. The equivalent conventional circuit is a parallel-tuned circuit, for it also has high resistive impedance at the resonant frequency.

The action of a quarter-wave section may also be explained as follows:



A section of line open at each end and less than a quarter-wave long acts like a *capacity.*



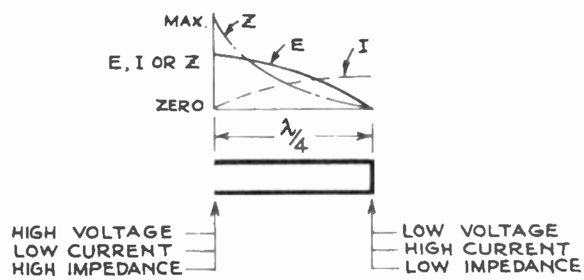
A section of line shorted at one end and less than a quarter-wave long acts like an *inductance.*

The capacitive reactance of a section of line one-eighth wave-long, open at the ends, is equal to the inductive reactance of a section of line one-eighth wave long, shorted at one end: The values of these reactances are equal to the "characteristic" impedance. (The "characteristic" or "surge" impedance depends on the size and spacing of the conductors.)

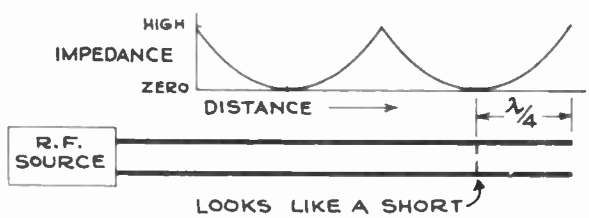
If the two sections are combined, the result is a resonant circuit that has high-resistive impedance, like a parallel-tuned circuit.

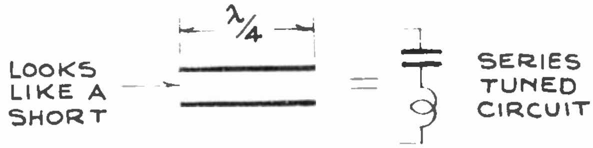
(This example is given because it is simple to visualize. Naturally, any two sections that add in length to equal one-quarter-wave electrically will have equal reactance and will produce the same result.)

The voltage, current, and impedance relations for a quarter-wave section are shown below:



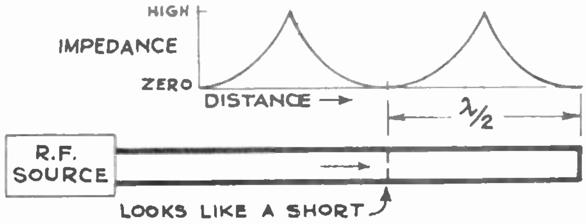
Quarter-Wave Open Section

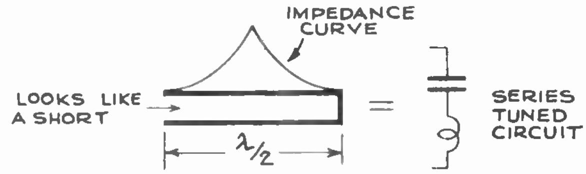




The quarter-wave section at the end of the line has very low input impedance, and, being tuned, it is resistive. It is equivalent to a conventional series-tuned circuit.

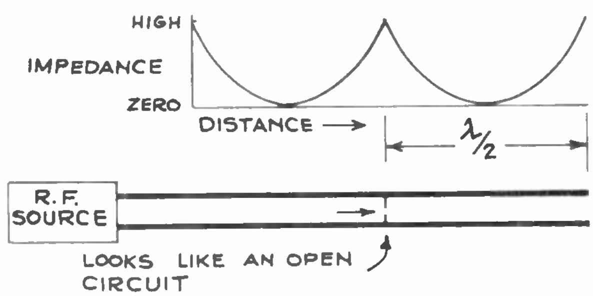
Half-Wave Shorted Section

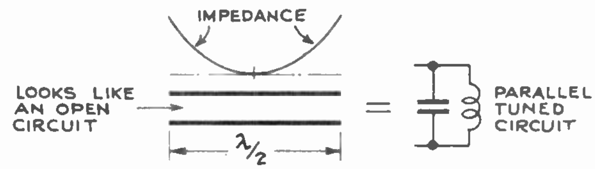




The half-wave shorted section at the end of the line also has low resistive input impedance. It corresponds to a series-tuned circuit.

Half-Wave Open Section





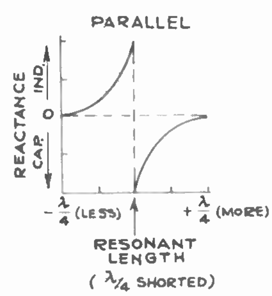
The half-wave open section at the end of the line has high input impedance. This section corresponds to a parallel-tuned circuit.

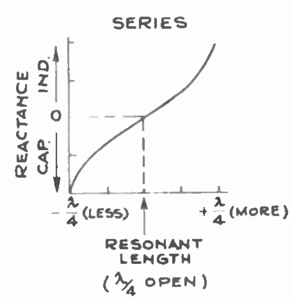
Tuning Characteristics of Resonant Sections

We have seen the four principal resonant sections:

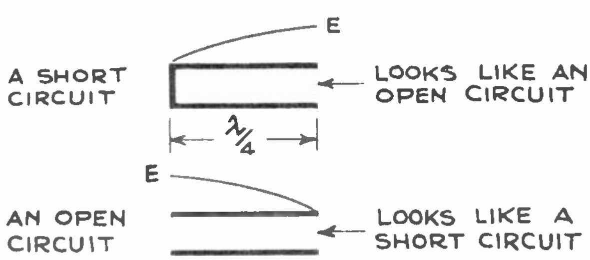
1. Quarter-wave, shorted } Equivalent to a par-
2. Half-wave, open } allel-tuned circuit
3. Quarter-wave, open } Equivalent to a series-
4. Half-wave, shorted } tuned circuit

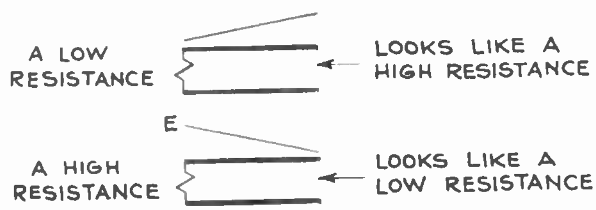
If a section of line is tuned above or below the resonant input frequency (by making the line shorter or longer) the effect is the same as in a conventional tuned circuit. The section will no longer look resistive. Either capacitive or inductive reactance will predominate. This is shown further in the tables on page 6 and in the graphs at right.





Quarter-Wave Line "Inverts" the Load





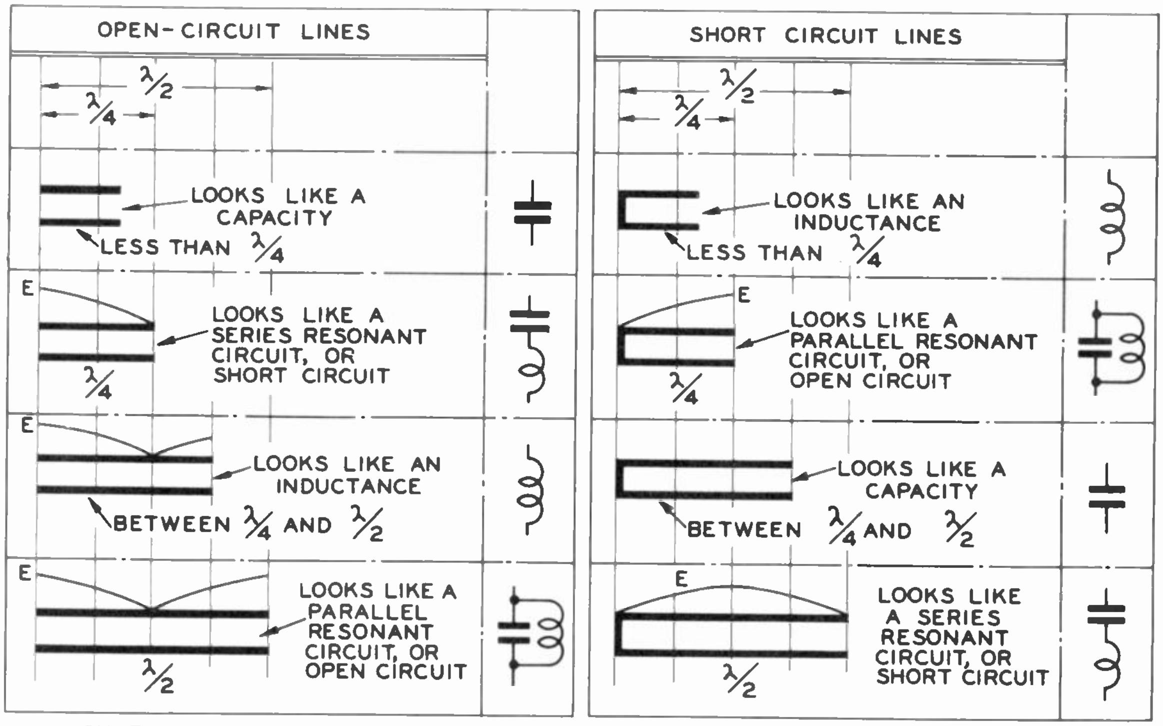
$$Z_o = \sqrt{Z_{IN} Z_{OUT}}$$

A quarter-wave line "inverts" the load as seen by source.

The input impedance in the above cases can be determined as follows:

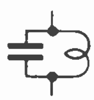
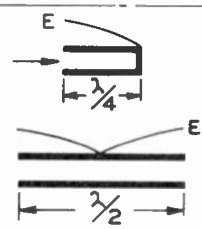
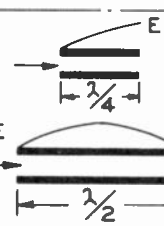
$$\text{Input impedance} = \frac{(\text{Line impedance})^2}{\text{Load impedance}}$$

Characteristics of Line Sections



CHARACTERISTICS REPEAT WHEN MULTIPLES OF AN ELECTRICAL HALF WAVE ARE ADDED.

Tuning Characteristics of Resonant Sections and Conventional Circuits

WHEN INPUT FREQUENCY IS CONSTANT, AND THE CIRCUIT IS ADJUSTED: ABOVE RESONANCE (SECTION MADE SHORTER) LOOKS LIKE	BELOW RESONANCE (SECTION MADE LONGER) LOOKS LIKE	CONVENTIONAL CURCUIT	RESONANT SECTION	WHEN THE CIRCUIT IS CONSTANT, AND THE INPUT FREQUENCY IS ADJUSTED: ABOVE RESONANCE LOOKS LIKE	BELOW RESONANCE LOOKS LIKE
INDUCTANCE ($X_C > X_L$)	CAPACITY ($X_L > X_C$)	 AT RESONANCE THESE CIRCUITS LOOK LIKE A HIGH RESISTIVE IMPEDANCE, OR "OPEN CIRCUIT"		CAPACITY ($X_L > X_C$)	INDUCTANCE ($X_C > X_L$)
CAPACITY ($X_C > X_L$)	INDUCTANCE ($X_L > X_C$)	 AT RESONANCE THESE CIRCUITS LOOK LIKE A LOW RESISTIVE IMPEDANCE, OR "SHORT CIRCUIT"		INDUCTANCE ($X_L > X_C$)	CAPACITY ($X_C > X_L$)

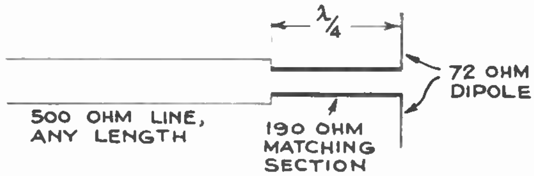
TUNED LINE CHARACTERISTICS REPEAT WHEN MULTIPLES OF AN ELECTRICAL HALF WAVE ARE ADDED

QUARTER-WAVE MATCHING SECTION

The "inverting" property of a quarter-wave section can be put to practical use when it is necessary to match a line of one impedance to a load of a different impedance. To do this, the section must have an impedance calculated as follows:

$$Z_{\text{MATCHING SECTION}} = \sqrt{Z_{\text{LINE}} \times Z_{\text{LOAD}}}$$

For example: A 500-ohm line can be matched to a 72-ohm dipole through a quarter-wave section of 190 ohms.



The *line* looks into a load of

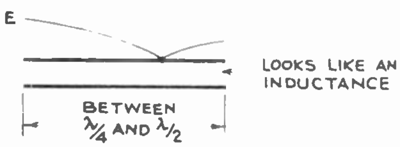
$$\frac{(\text{Z of matching section})^2}{\text{Z of load}} \text{ or 500 ohms.}$$

The *antenna* looks into a source of

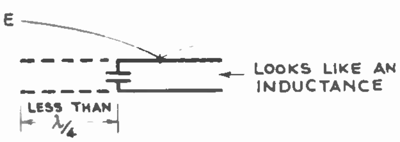
$$\frac{(\text{Z of matching section})^2}{\text{Z of line}} \text{ or 72 ohms.}$$

"INVERSION" OF CAPACITY AND INDUCTANCE

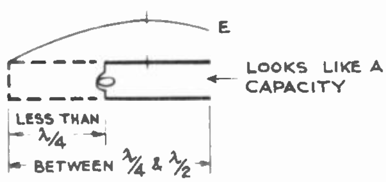
Inversion of capacity and inductance can be explained as follows:



An open section of line between one-quarter and one-half wave long looks like an inductance to the source.

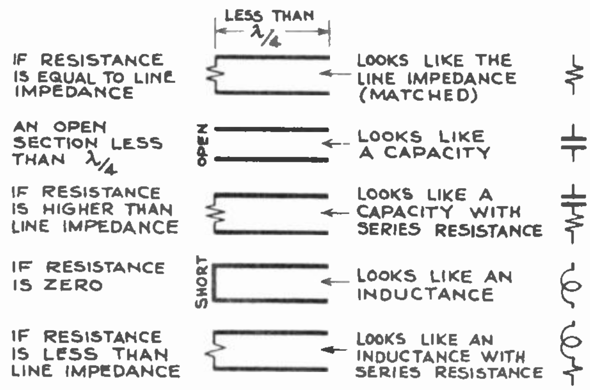


If a part (less than one-quarter wave) is replaced by a capacity (an open section less than one-quarter wave looks like a capacity), the section still looks like an inductance to the source.

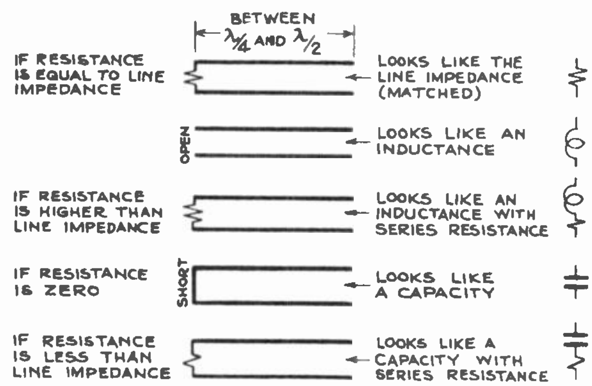


A shorted section between one-quarter and one-half wave looks like a capacity. If part (less than one-quarter wave) of the shorted end is replaced by an inductance, the section will still look like a capacity to the source.

SECTIONS LESS THAN QUARTER-WAVE

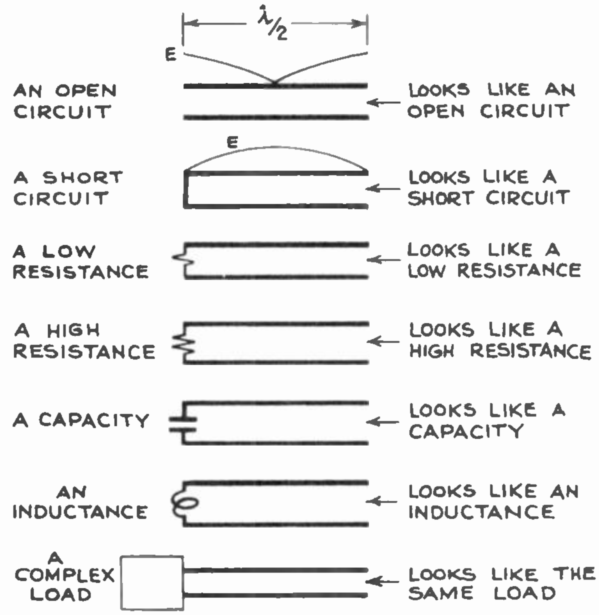


SECTIONS BETWEEN ONE-QUARTER AND ONE-HALF WAVE



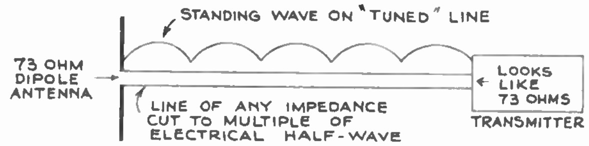
HALF-WAVE LINE "REPEATS" THE LOAD

A half-wave line acts as a "double inverter" and hence will "repeat" whatever appears on the far end:



A line that is any multiple of one-half wave has the same characteristics.

The action of a half-wave section, or a line cut to a multiple of a half-wave, is used extensively in practical applications. For example, if a dipole antenna with an impedance of 73 ohms is to be coupled to the output of a transmitter, through an open-wire line (spaced pair) with a characteristic impedance of several hundred ohms, the line can be cut to a multiple of an electrical half wave.



The transmitter will look into a load of 73 ohms, regardless of the impedance of the line.

"Tuning Out" the Reactance of a Load

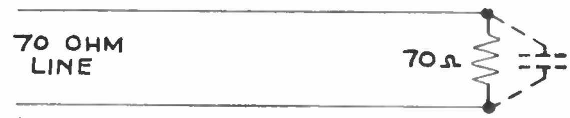
One of the important applications of tuned-line sections is to "tune out" the effects of residual capacitive or inductive reactance in a load, so the load will look like a pure resistance.

For example, assume that a 70-ohm resistor is used to terminate a 70-ohm line. If this line, with its resistor termination is connected to a slotted line and checked for match over a wide range of frequencies, it will be found that at some frequency the termination looks resistive. This is the resonant frequency of the resistor. Above and below this frequency the resistor has capacitive or inductive reactance and no longer matches the line. In other words, the resistor is not a "pure resistance" at most frequencies.

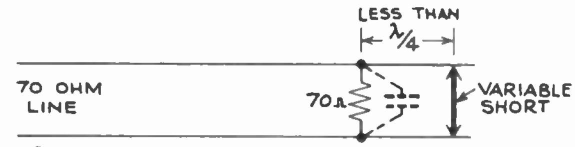
At the required operating frequency, the resistor may look like a resistance with shunt capacity as shown in "A." If an inductive section of line is connected to the termination as shown in "B," it may be adjusted to resonate with the capacity, to look like a parallel-tuned circuit.

The line, therefore, instead of seeing a resistance with shunt capacity, now sees a resistance with a shunt parallel-tuned circuit, as shown in "C."

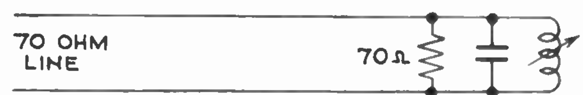
The parallel-tuned circuit looks like a high resistive impedance as shown in "D," and, therefore, has little effect on the total resistance. If the combined resistance is correct, the line will be "matched."



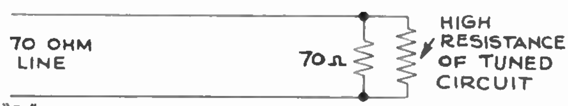
"A"- RESISTOR WITH RESIDUAL CAPACITIVE REACTANCE.



"B"- INDUCTIVE SECTION ADDED AND RESONATED WITH CAPACITY TO THE INPUT FREQUENCY.



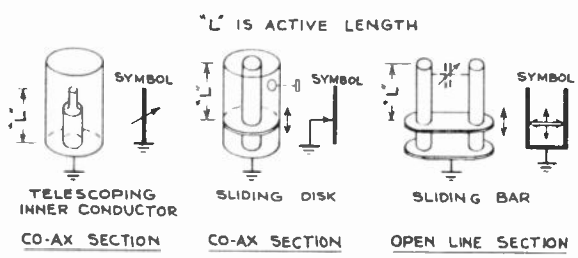
"C"- EQUIVALENT CIRCUIT OF "B"



"D"- LINE NOW LOOKS INTO 70 OHM SHUNTED BY HIGH RESISTANCE.

Tuned-Line Sections—Types of Construction

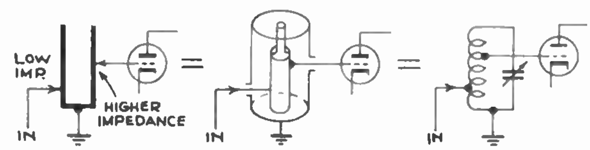
The characteristics of tuned lines are used to good advantage in UHF equipments. Quarter-wave and half-wave sections are used as parallel- and series-tuned circuits, as step-up and step-down transformers, as impedance and phase inverters, and even as insulators. Such sections of line take the place of conventional tuned circuits which become too small and inefficient at ultra-high frequencies. The tuned-line sections are made in both co-axial form, and in open-line type, from metal tubes and rods; generally silver-plated to reduce r-f losses. Some representative types of construction are sketched at left. Methods of adjustment to resonate the sections are indicated.



Some sections are cut short, and resonated with an adjustable capacitor (indicated by dotted lines) instead of being resonated with a sliding disc or bar.

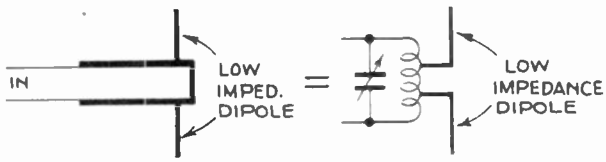
Quarter-Wave Sections as Transformers

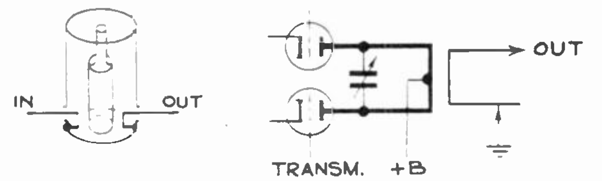
A quarter-wave section (co-ax or "open-line" type) shorted at the end, may be used as a step-up transformer, similar to a parallel-tuned auto-transformer. When a resonant section is "loaded" with reactance, for example, connected to the grid of a tube, the section must be readjusted to obtain electrical resonance).



A quarter-wave shorted section may be used as a step-down transformer.

Inductive coupling to tuned sections is sometimes done as shown in the following two different examples:





Co-Ax Arms on Tuned Sections

In push-pull UHF circuits, lengths of co-ax are frequently used to form the arms of one-quarter or one-half wave shorted sections. This is done for several reasons, including:

(1) The inner conductors may be used to carry d-c and a-c supply voltages, or low-frequency signals, to the tube elements.

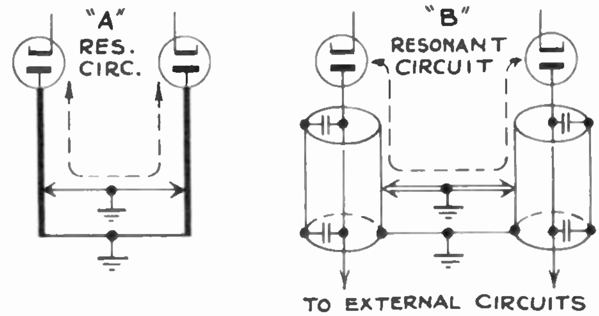
(2) The outer conductors can be grounded.

(3) A sliding bar on the outer conductors can be used to adjust the electrical lengths of the section mentioned in (1) above.

In such applications, capacitors are used at the end of the co-ax to place the inner and outer conductors at the same r-f voltage.

An example of co-ax arms forming tuned sections is shown in the illustration.

"A" is the quarter-wave shorted section required for input tuning. But it is necessary to take the diode currents to external circuits, and (for constructional reasons) the arms of the section must be grounded. "B" shows how "A" is rearranged to do this. *The co-ax lines do not act as tuned sections by themselves, but form the arms of the quarter-wave shorted section shown in "A."*



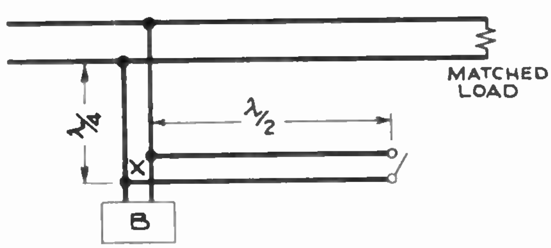
Miscellaneous Application of Tuned Sections

Tuned sections are put to many uses in addition to that of replacing conventional tuned circuits.

Some miscellaneous uses are described to indicate several of the many applications.

(1) Use of Sections in Switching Circuits

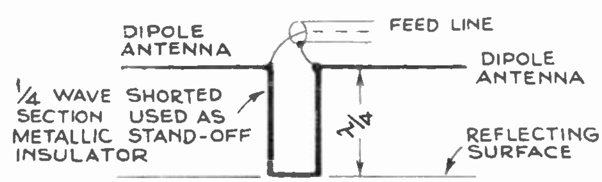
In some equipments it is necessary at times to prevent signals from "A" getting to "B." This is accomplished by shorting the end of the one-half wave section. By virtue of the action of one-half wave sections, this short appears as a short across "B" input line at "X." The one-quarter-wave line, being thus shorted at "X," looks like a high impedance to the signal from "A."



When it is desired to leave signals through to "B," the switch is opened at the end of the one-half-wave line. At "X," the one-half-wave resonant line now looks like an open circuit. With no short at "X," the one-quarter-wave section is simply an ordinary part of the line, and signals can pass to "B."

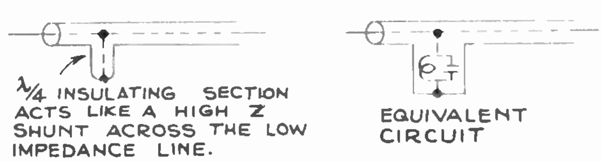
(2) Quarter-Wave Shorted Section Used as an Insulator

(a) A quarter-wave shorted section looks like a high resistive impedance. This fact is utilized in some antenna systems by employing one-quarter-wave shorted sections as metallic stand-off insulators to support and space a dipole antenna one-quarter wave from a reflecting surface, as shown below:



The quarter-wave section looks like a high impedance to the antenna feed line. (The feed line can be run inside one arm of the quarter-wave section.)

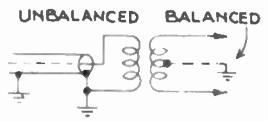
(b) Another example of a quarter-wave "insulator" is shown below, together with an analogy of a conventional parallel-tuned circuit.



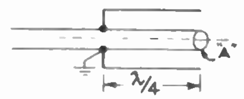
(3) Line Balance Converter (Bazooka)

In some applications, it is necessary to change from a co-axial transmission line (unbalanced, since outer conductor is grounded) to a balanced transmission line or load (both conductors approximately the same impedance above ground).

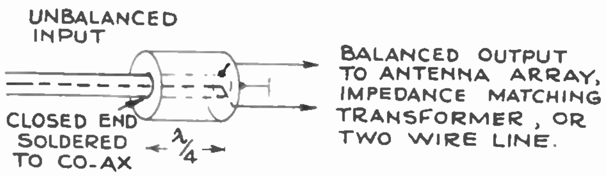
A "bazooka" is used for this purpose. The action is shown in the sketches, and may be explained as follows:



PRINCIPLE OF CONVERTER



BAZOOKA FORMS SHORTED QUARTER WAVE SECTION PLACING "A" AT HIGH Z TO GROUND.



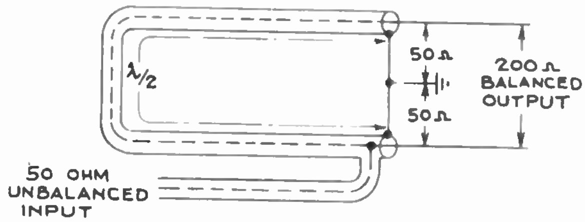
1. The quarter-wave shorted section effectively removes the r-f ground from the end of the outer conductor of the co-axial line.

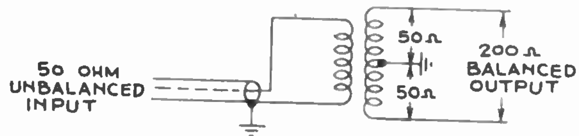
2. Both the inner and outer conductors of the co-axial line are now at a relatively high impedance above ground, and effectively balanced to ground.

3. The bazooka may be used in reverse manner to feed from a balanced circuit to an unbalanced circuit.

(4) Half-Wave Phase and Impedance Converter

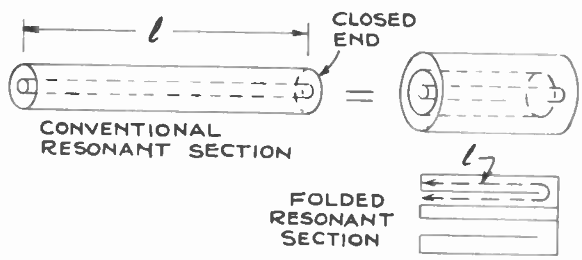
The following arrangement is used in some applications. The action may be reversed, to feed from high-impedance balanced input to low-impedance unbalanced output.





(5) "Folded" Resonant Section

At relatively low frequencies, the physical length of a resonant section may be too long for convenient use, and a "folded" section may be used. The effective length of the folded section is indicated by the dotted line. More than one "fold" may be used for further reduction of the physical length.



Characteristic Line Impedance

The impedance of a line (also termed "surge" or "characteristic" impedance) depends on the dimensions and spacing of the conductors, and the dielectric constant of the insulating material.

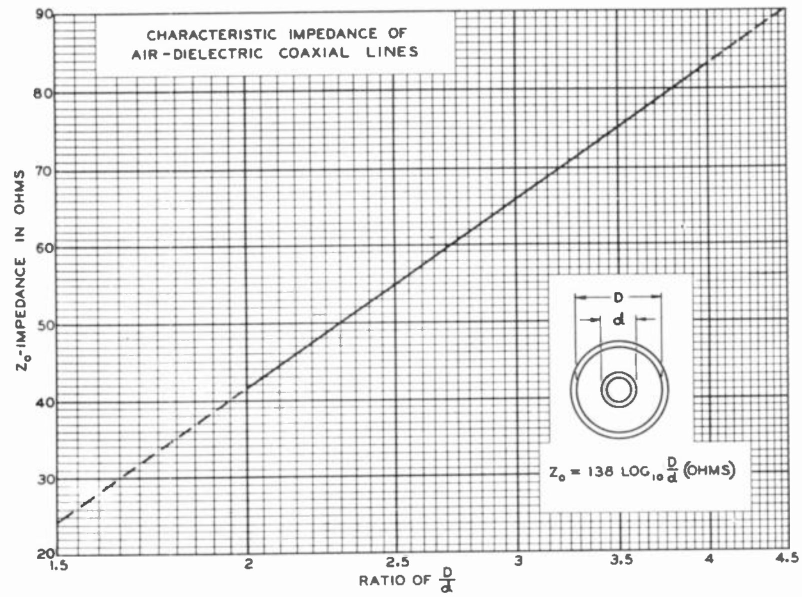
Neglecting Losses—

$$Z_{OHMS} = \sqrt{\frac{L_{HENRYS}}{C_{FARADS}}}$$

In solid dielectric lines (as compared with air dielectric) the impedance is reduced by the factor $\sqrt{1/k}$, where "K" equals the dielectric constant of the insulating material (and has the effect of increasing "C" per unit length in the general formula).

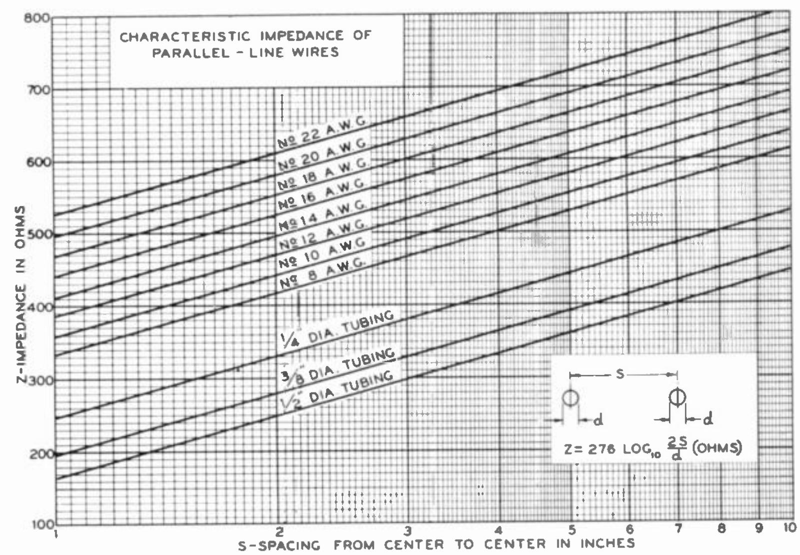
Aircraft Antenna Cable, using solid dielectric is frequently 70 or 50 ohms. Seventy (70)-ohm cable is convenient for use with quarter-wave dipoles and other antennas that have a radiation resistance of 70 ohms. Fifty (50)-ohm cable is used extensively in conjunction with suitable matching on low-impedance array-type antennas.

The two charts on the following page show how the impedance of co-axial and parallel-wire lines varies with the dimensions and spacing of the conductors.



Impedance chart for air-dielectric co-axial lines.

Example: For a 50-ohm line, "D" is 2.3 times larger than "d". For a 70-ohm line, "D" is 3.2 times larger than "d".



Impedance chart for parallel-wire lines.

Example: To obtain a line impedance of 500 ohms, using No. 14 wire, the spacing (S) must be approximately 2 inches.

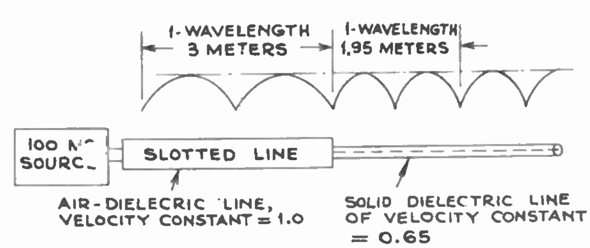
Velocity Constant of Lines

Radio waves travel at a speed of 300 million meters per second in air. The speed is reduced in lines that have spacing insulators or solid dielectric. In a slotted measuring line, with no spacing insulators, the speed is essentially the same as in air.

The speed in solid-dielectric lines of high quality, such as UHF aircraft antenna cable, is about 60-70 per cent of speed in air. Reels of such cable are tagged with the measured velocity constant of a sample cut from the reel.

The fact that the velocity is less in the cable than in air means that a wavelength in the cable will be shorter than in air; since the wavelength equals velocity divided by frequency. For example, a wavelength in air at 100 mc. is 3 meters, but in a solid-dielectric cable with a velocity constant of 65 per cent, a wavelength at 100 mc. is only 3 x .65, or 1.95 meters.

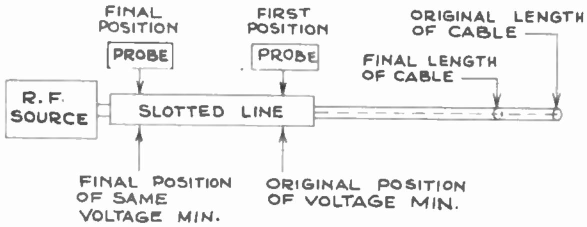
The lower velocity in solid-dielectric lines is illustrated below. A 100 mc. signal is fed through a



slotted line (air dielectric) and into a solid dielectric line that has a velocity constant of 0.65 (65 per cent of that in air).

A slotted line can be used to check the velocity constant of a co-ax cable.

The equipment is set up as shown:



The end of the cable is left open. Standing waves are therefore set up along the cable and slotted line. The probe is set accurately at the first point of minimum voltage at the cable-side of slotted line. A piece of cable is cut off at the end of the line. This shifts the voltage minimum point to the left, and the probe is reset accurately to the new position of the voltage minimum.

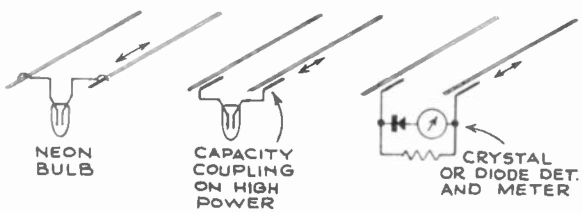
The ratio of the length of the piece of cable cut off to the distance that the probe is moved is the velocity constant of the cable. (In practice, small increments of cable are cut off until nearly the entire length of the slotted line has been traversed by the probe. Each step is plotted, and the slope of the line indicates the velocity constant).

As an example, if the length of cable cut-off is 1 foot, and the probe has been moved 2 feet, the velocity constant is .5, or 50 per cent.

Standing-Wave Indicators for Open-Wire Lines

A small neon bulb may be used to show existence of standing waves on open-wire lines. If the line is correctly terminated (no standing waves) the bulb will have constant brilliance as it is moved along the line.

Better indication can be obtained by using a crystal or diode rectifier and a meter, capacitively coupled to the line as shown.



Slotted Measuring Line

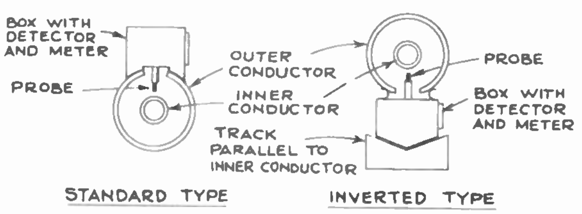
A "slotted line" is a section of co-axial line with a slot along the outer tube to permit loosely coupling an r-f voltmeter probe to the inner conductor.

The slotted line is used to determine:

(1) Ratio of voltages at maximum and minimum voltage points of standing waves along the line.

(2) Position of these points with respect to a "Reference" point.

From this data it is possible to determine the resistive and reactive nature of a load at a specified frequency.



Some Principal Applications Are

(1) To adjust antennas for correct match to a line at a specified frequency.

(2) To determine the resistive and reactive components of a load at a specified frequency, or over a range of frequencies; i. e., impedance and phase angle.

(3) To adjust input systems of receivers, dummy loads, etc., for correct match to a line.

Considerable care is taken in the design and construction of slotted lines to secure:

(1) Uniform impedance throughout the length.

(2) Uniform spacing of the probe in its travel along the inner conductor.

(3) Good grounding of the probe box to the outer conductor.

(4) Rigidity of the co-ax assembly, and minimum slop in travel of the voltmeter probe.

The impedance of the slotted line should equal the impedance of the associated co-ax line. Some slotted lines are equipped with two or more mechanically interchangeable inner conductors of different diameters so the impedance can be changed to match the impedance of commonly used co-ax lines (70 and 50 ohms, and some 63 and 40 ohms).

The r-f voltmeter used in conjunction with the slotted line is usually a diode or crystal detector with a current meter and tuned input, capacitively coupled to the inner conductor.

Diode and crystal detectors are insensitive and require a high-output UHF oscillator to excite the line. It is sometimes possible to use the UHF receiver (from an equipment) as an indicator, fitting the input of the receiver with a suitable probe. In this case, owing to the high sensitivity of the receiver, a low-powered UHF generator may be used for the source.

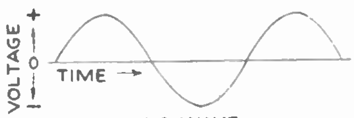
When adjusting antennas, the object in most cases is to "match" the antenna to the line. This is usually done by changing the antenna length and/or the antenna matching stub for *minimum* standing-wave ratio.

For some antennas, and in other applications of the slotted line, it is necessary to determine the resistive and reactive components and phase angle.

This requires checking both the standing-wave ratio and the distance from a minimum (or maximum) voltage point with respect to a "reference" point. This subject is covered in the appendix.

Additional Data on Standing Waves

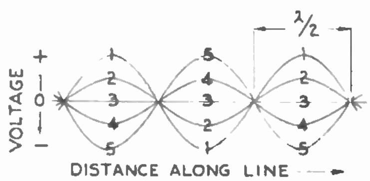
An a-c wave may be drawn as a change in *voltage* during a period of *time*, as shown below.



AC WAVE

A standing wave is not as easy to show, because it involves changes in *voltage* with *time*, and with *distance* along the line.

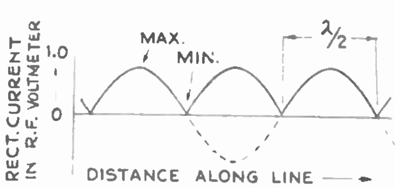
The voltages between node points of a standing wave changes from positive to negative values and back during the time equivalent to one cycle of the r-f source. This r-f change in voltage is roughly indicated by curves 1 to 5 and back in the following sketch.



STANDING WAVE

At some instant, the voltage along the line may be shown by one of these curves. It will be noted that the term "standing" wave can be misinterpreted. In a standing wave the *position* of max. and min. points does stand still, but the voltage changes at the r-f rate.

When an r-f voltmeter is moved along the line, it indicates the relative amplitude of the r-f voltage variation at each point along the line. The rectified r-f current in the meter circuit may be zero at nodes, and increases to a max. when the r-f voltmeter is moved to each voltage max. point. Thus the *measured* standing wave appears as shown below. (This is a sine wave with the negative half-cycles "flopped up.")

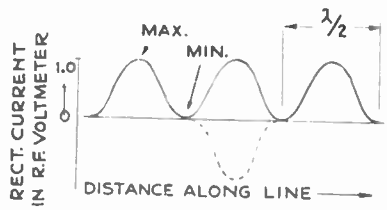


By turning one of the half-cycles down, as shown in dotted lines, it will be seen that the curve is a sine wave.

The standing wave that exists on the line is a sine wave, providing the r-f source is sine wave; that is, a fundamental frequency with no harmonics. For slotted-line measurements, the generator must furnish sine wave output. If harmonics are present, some of the min. points, with the line open or shorted will not be zero.

If the standing wave on the line is sine wave, the *measured* standing wave will be sine wave, providing the r-f voltmeter is *linear.*

If the rectifier in the r-f voltmeter is not linear, the measured standing wave will not be sine wave, but will appear as shown.



By turning one of the half-cycles down, as shown in dotted lines, it will be seen that the standing wave, as measured with a non-linear detector, is far from being a sine wave.

It will be noted that with a non-linear detector, the voltage min. points are not as "sharp" as indicated in the preceding illustration, which shows a standing wave measured with a linear detector.

The graph on page 24 shows how a non-linear detector introduces distortion in measuring a sine wave standing wave.

This non-linearity causes error in measuring standing wave ratios. In some applications of the slotted line, as for example when adjusting an antenna to "match" the line, this error may be ignored.

In other applications where it is necessary to determine the standing wave ratio accurately, correction can be determined in this way:

1. Plot the standing wave as measured with *the particular detector* at the *desired frequency,* with the line open or shorted, and with the generator output adjusted for exactly full-scale deflection at the max. voltage points.

2. Construct a sine wave (half-cycle) on top of the measured standing wave, with zero and max. points coinciding as shown in the graph on page 24. The sine wave indicates the current that would flow if the detector were linear.

Assume that a particular load produces a standing wave with a measured ratio of

$$\frac{\text{VOLTAGE MIN.}}{\text{VOLTAGE MAX.}} = \frac{0.21}{0.6} = 0.35$$

Reference to the curve shows that the value of 0.21 on the *measured* curve corresponds to 0.39 on the sine wave curve.

Also the value of 0.6 on the measured curve corresponds to 0.71 on the sine wave curve. The corrected standing wave ratio is therefore

$$\frac{0.39}{0.71} = 0.55 \text{ (instead of 0.35).}$$

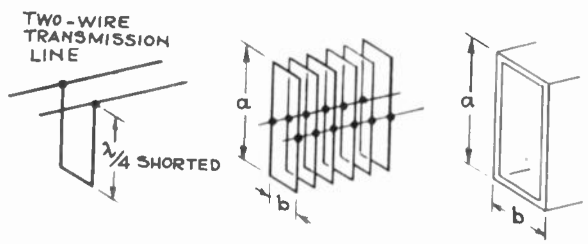
Wave Guides

A wave guide is a simple hollow metal tube having no central conductor. The losses are relatively low, since they will be produced mainly by the "inner skin" of the tube (which is of large perimeter and hence gives low loss). The *inner surface* should be clean and smooth. The *outer surface* can be grounded at any point since the r-f penetrates only a thin skin of the inner surface. *Sharp bends* are usually avoided, and all bends and twists are arranged to prevent a change in "mode" of propagation, or reflections. Instead of a hollow metal guide, a *solid dielectric* may be used as a wave guide. The action in this case is comparable to light waves traveling inside a *lucite rod.* In general, the loss in a solid dielectric wave guide is greater than in a hollow wave guide.

A wave guide cannot be conveniently treated like an ordinary transmission line. Wave guides must be approached from the viewpoint of an electromagnetic wave in a dielectric, using the same basis of treatment as that of radiation.

Wave guides may be rectangular, round, or oval. At the present time, rectangular wave guides are most simple and common; this discussion will refer to rectangular wave guides for the most part, but much of this information can be extended to guides of other shapes.

The following development of a simple type wave guide is intended to serve as a means of bridging the gap between transmission lines and wave guides, although they operate on different principles.

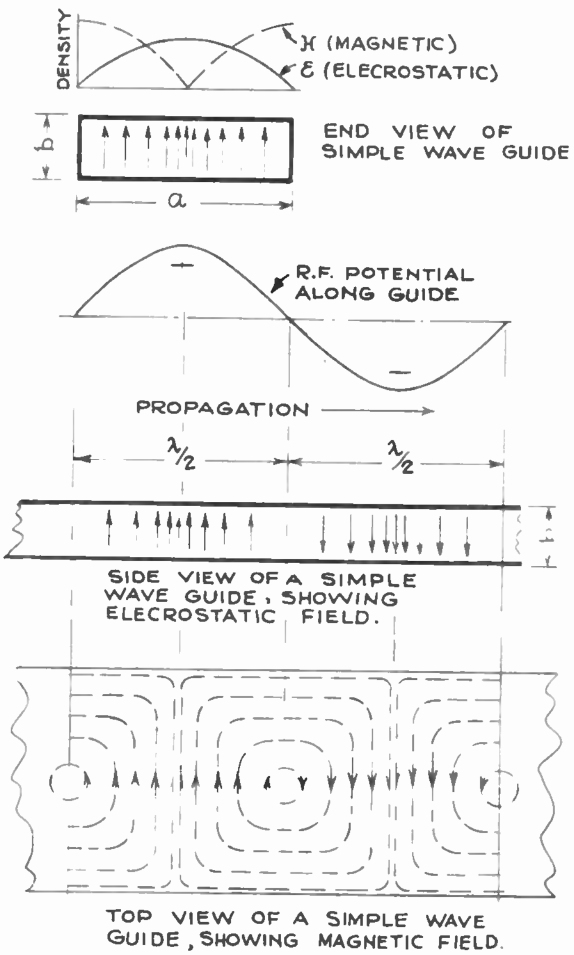


Above at left is shown a section of two wire transmission line. A quarter-wave resonant stub has been added across the line. The ends of the stub where connected to the transmission line, will represent a high impedance—many times higher than the impedance of any practical two wire transmission line. As a result the stub will have a negligible effect.

Suppose an infinite number of quarter-wave shorted stubs are added, resulting in a continuous pipe of rectangular cross section, or one type of wave guide. See illustration above.

"a"—Has a minimum dimension of half a wavelength (in order to propagate a signal) but it may be greater. The "cut-off" frequency depends on dimension "a".

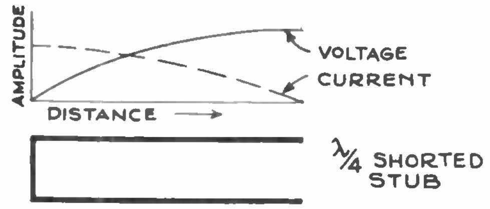
"b"—Is not critical except for voltage breakdown or the possibility of operation in a wrong "mode".

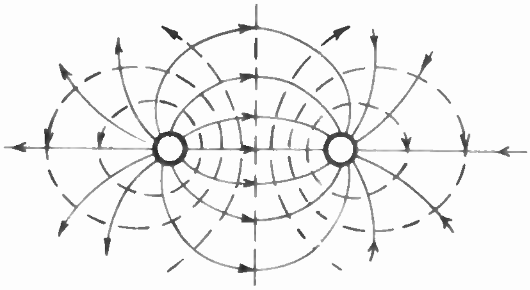


WAVE-GUIDE FIELDS

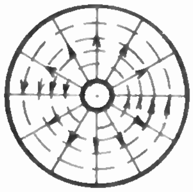
For a simple rectangular wave-guide, the electrostatic lines of force and density of distribution of the E & H fields are shown in the illustration. The electro-magnetic lines of force may be thought of as "whirlpools" in a plane, perpendicular to the electro-static lines of force, traveling down the tube in the direction of propagation. A rectangular wave guide will transmit satisfactorily if the component of the electric field tangent to the side surface is zero at every point on the surface.

A two-wire and a co-axial transmission line are shown with the magnetic and electrostatic fields indicated. A transmission line may be thought of as a guide for magnetic and electrostatic fields.





FIELDS ABOUT TWO-WIRE LINE



FIELDS IN A CO-AXIAL LINE

– – – – H OR MAGNETIC FIELD DUE TO CURRENT IN CONDUCTOR.

———— E OR ELECTROSTATIC FIELD DUE TO VOLTAGE BETWEEN CONDUCTORS.

TRANSMISSION LINE FIELDS

TYPES OF PROPAGATION

"TM" propagation refers to *transverse-magnetic*, and is applied to the fact there is no magnetic field (H) in the direction of propagation down the tube. The electric field (E) does have a longitudinal component in the direction of propagation. There are numerous modes of operation (or oscillation) depending upon the cross section of the hollow metal tube and how it is excited from the r-f source. Different modes of operation are identified by sub-numerals after the letters "TM."

"TE" propagation refers to *transverse-electrostatic*, and is applied to the fact that the magnetic (H) field is in the direction of propagation and the electric (E) field is transverse. There are numerous modes of operation; identified as mentioned in the paragraph above. It may be of interest to note that "TEo" mode has the lowest "cut off" frequency of any that can be transmitted through a given tube. The fields shown in this booklet are TEo-1.

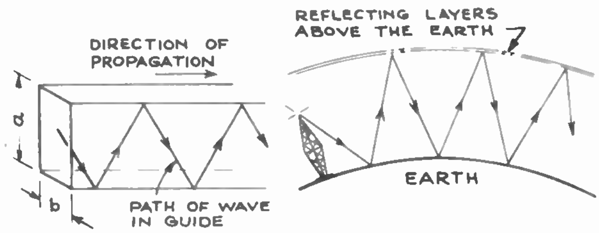
TRANSMISSION OF R-F ENERGY IN WAVE GUIDES

Electro-magnetic fields may be propagated down a hollow metal tube provided:

1. The frequency is high enough.
2. The fields have certain definite distributions.

Wave Guides are essentially ultra-high frequency devices since the frequency must be high before a field can be transmitted (from a practical point of view) through a wave guide. A wave guide has a definite cut-off frequency, as determined by the cross section of the hollow tube, and will not operate at a frequency lower than the cut-off frequency. When the guide is half a wavelength in width (dimension "a") the wave reflects back and forth across the guide making no progress at all (hence cut-off frequency). It may be considered that the wavelength of the r-f energy must be short enough to fit into the cross-sectional dimensions of the wave guide.

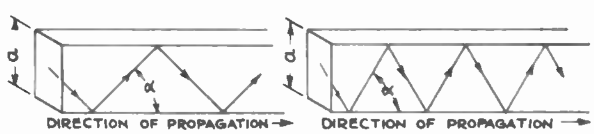
The velocity of propagation (group velocity) of r-f energy in a wave guide is *slower* than the speed in air. This is due to the fact that the wave does not travel straight through the guide, but is reflected from wall to wall. The length of the path that the wave travels is longer than the actual length of the guide. This action is comparable to the reflection of radio waves by ionized layers above the earth as illustrated.



The group velocity is dependent on the frequency and the tube dimensions (dimension "a" in a rectangular guide). For a given size of rectangular guide, the group velocity—

(1) Increases as the wavelength becomes shorter since there are fewer reflections from the wave-guide walls for a given amount of forward travel (see illustration "1") but is always less than the speed of light.

(2) Decreases as the wavelength becomes longer (up to the cut-off frequency) since there are more reflections from the wave-guide walls for a given amount of forward travel (see illustration "2").

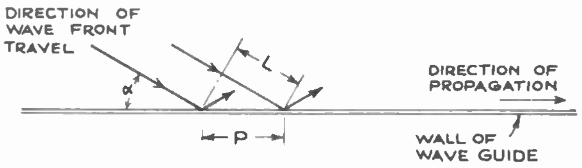


1- SHORTER WAVELENGTHS 2- LONGER WAVELENGTHS

Phase Velocity (apparent speed) is greater than the speed of propagation; or the speed of travel in an unrestricted medium.

$$\text{Apparent speed} = \frac{\text{(true speed)}}{\text{(cos } \alpha \text{ between wall and direction of travel.)}}$$

Thus the apparent speed is greater since the waves are striking the wall at an angle.



In the time required for the wave front to move the distance "L", the point of reflection has moved the greater distance "P". Thus the apparent speed (phase velocity) is greater than the true velocity of propagation.

The wavelength in a hollow wave guide (as measured on a slotted wave guide) is always greater than, or at the limit equal to, the wavelength in air.

Attenuation in a rectangular wave guide of given size varies as follows:

(1) As the wavelength of the signal increases toward the cut-off value, the attenuation increases since there are more reflections resulting in higher losses due to r-f currents in the "skin" of the inside wall.

(2) At a much shorter wavelength, attenuation again increases due to increased "skin effect" at higher frequencies (except in a special case where the electrostatic field does not terminate on the wall of the guide).

(3) There is an *optimum* frequency of least attenuation; however, this is usually not used because of economy reasons.

The characteristic impedance is different for every mode of *operation*. In a round wave guide the lowest characteristic impedance is about 350 ohms. In a rectangular wave guide the characteristic impedance may be any value as both dimensions are varied. The impedance is directly proportional to the narrow dimension "b" and if the other dimension "a" and the frequency are fixed, the impedance may be any value between approximately 0 and 465 ohms. The impedance approaches zero as the narrow dimension "b" is reduced.

The "Q" of a wave guide is a function of frequency. It is also directly proportional to the ratio of volume to inside area of the guide. "Q" may be of the order of 25,000.

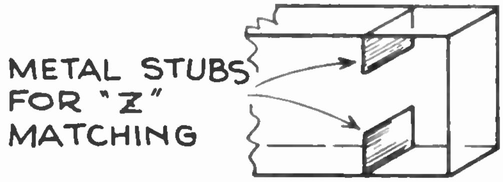
Practical Facts About Wave Guides

1. An electrical quarter-wave length or odd multiples of a quarter-wave length, wave guide *shorted*, reflects an "*opening*" where it joins another wave guide.

2. An electrical half-wave or multiples of a half-wave *shorted* reflects a "*solid wall*" where it joins another wave guide.

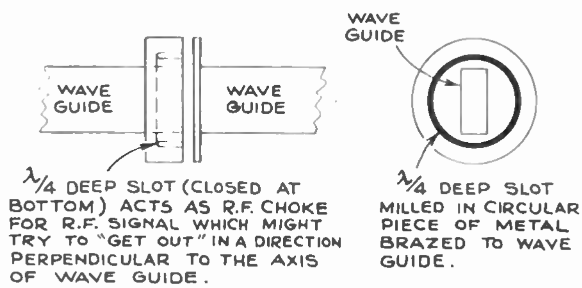
3. A quarter-wave section of wave guide inverts the impedance as with ordinary forms of transmission line.

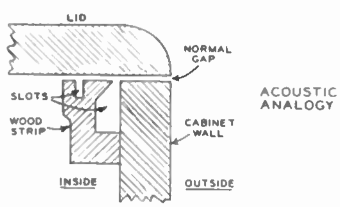
4. A wave guide has a "characteristic impedance" which is usually rather high compared with the impedance of co-axial lines.



5. Impedance matching may be accomplished by using "shorting stubs." For instance, in matching to a dipole radiator. The stubs constrict the opening; may be used to "filter" out certain modes of operation.

6. Usually where two wave-guide sections are joined in such a fashion, as to be quickly removable, an r-f choke is used.



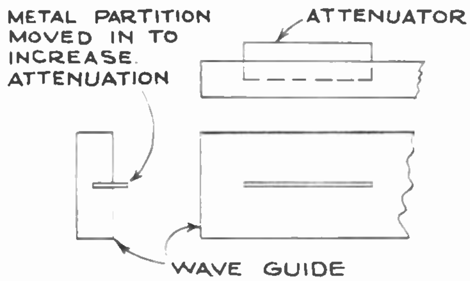


An acoustic analogy (RCA "Tone Guard") is shown above. The slots around the inside of the cabinet act as chokes to prevent undesired high-frequency sound (that is radiated by the vibrating parts of the phonograph pickup) from "getting out" through the normal gap between the lid and the cabinet.

7. For some purposes, usually test, a wave guide may be matched to air by increasing the internal cross section of the guide slightly at the "air" end; normally an r-f choke, as shown above, is also used.

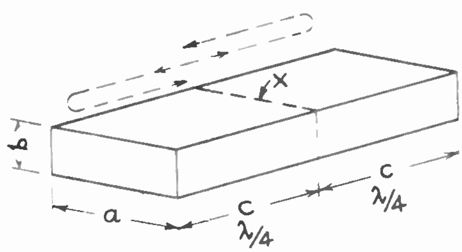
The end of the wave guide may also be flared outward (increasing the cross section) and used for radiation.

8. A wave-guide attenuator may consist of a movable metal partition as shown below; the attenuation increasing as the partition is moved in.



9. Standing-wave ratios are checked in a manner similar to that used for a co-axial line. A section of wave guide with a narrow slot parallel to the axis of the wave guide (located in the maximum of the electro-static field) is used. A probe with a "crystal detector" or an instrument fuse (1/200A heated to almost the blowing point by d-c) is used to detect the presence of standing waves, as with a slotted co-axial measuring line. Due to the much higher frequency, measurements are considerably more delicate.

10. A section of wave guide may be used as a tuned circuit or as a transformer. In the accompanying illustration, if r-f energy is introduced at "X," reflection will occur at the closed ends. If dimension "C" is correct, the r-f voltage will be reinforced at "X." In this example "C" is a quarter of a (guide) wavelength, however other lengths may be used as long as the reflected voltage arrives back at "X" in phase with the r-f source.

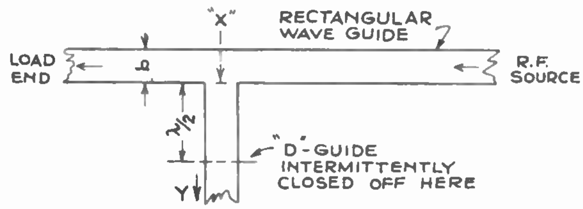


The resonant effect is due to reflections (from the closed ends) setting up standing waves in the guide. The action is similar to that of a "cavity resonator."

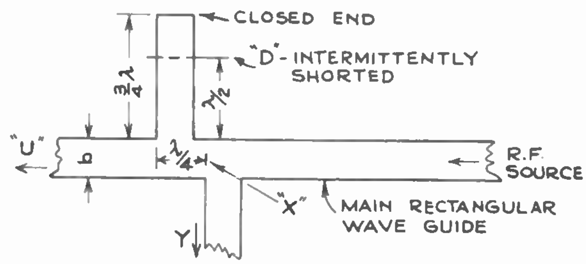
The r-f energy may be introduced inductively, capacitively, or by radiation. Output may be obtained in a similar manner.

11. Sections of open and closed wave guides may be used in switching circuits, etc. In the following examples where a quarter or three-quarters wavelength is indicated, any odd multiple of a quarter wavelength may be used. Where a half wavelength is indicated, any multiple of a half wavelength may be used. (Electrical wavelength in the guide is referred to, not physical length).

In the illustration below an intermittent short at "D" (mechanical or by means of a special tube) is used. A short at "D" will result in effectively a "solid wall" looking in at point "X" when "D" is shorted.



In the following illustration an intermittent short at "D" (mechanical or by means of a special tube) is used.



When "D" is shorted, effectively a "solid wall" will result at the junction of the closed stub to the main wave guide. Paths "Y" and "U" may receive energy.

When "D" is not shorted, effectively a "solid wall" will result looking in at point "X" which is two half waves (a full wave) from the closed end. There will be no transmission in the direction "U" but there will be transmission in direction "Y."

12. A typical wave guide in practical use now, which happened to be a standard size of rectangular tubing:

Width—about 1.5% greater than a half wavelength (about as small as can be used).

Thickness—about 44% of the width.

Wavelength—about 40% longer than in air (standing-wave measurement).

Loss—about 1/10 db per meter correctly matched).

Standing Wave Ratio—of as high as 3 to 1 may be tolerated.

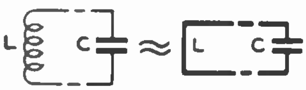
Cavity Resonators

Cavity resonators are tuned resonant circuits for extremely high frequencies where it becomes impossible or impractical to use tuned lines or lumped circuits.

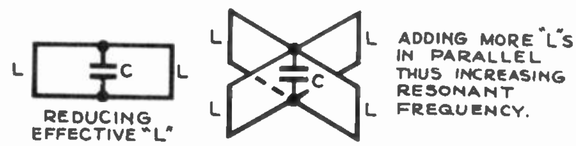
No unique definition of L, C and R can be found in a cavity resonator. A cavity resonator is similar to a wave guide in that electro-magnetic lines of force oscillate back and forth within the cavity in some particular mode, depending upon the shape and method of excitation of the cavity.

UHF cavity resonators may be compared to conventional acoustic resonators. An example is the boomy sound in a room with smooth hard surfaces (good acoustic reflectors). Sound from a source will be reflected from wall to wall with only slight absorption of energy at each reflection. If the frequency of the sound is such as to produce standing waves between two surfaces, or combination of surfaces, the sound is reinforced. The resonant frequency depends on the room dimensions. The "Q" depends on the reflectivity of the walls and other losses.

Developing a Simple Resonant Cavity



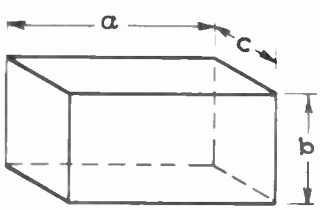
WHERE $f_R = \frac{1}{2\pi\sqrt{LC}}$



If it is desired to increase the resonant frequency, we can parallel the inductances "L," thus making the equivalent "L" quite small. There are limits as to how small "C" may be made practically, so the only thing left to do is to decrease the effective "L" of the circuit in order to tune to a higher frequency. See diagram at right.

As shown at the right above, more and more inductive stubs may be added, thus decreasing the effective "L" and increasing the resonant frequency. If this is carried on to the extreme, a closed chamber or resonant cavity results. (Strictly speaking, it is not proper to talk of the inductance of a cavity resonator.)

Modes of Operation of Cavity Resonators



Consider a rectangular section. The description of the "Mode" would be given in terms of electro-magnetic fields and various frequencies. Various frequencies of oscillation (different modes) are possible, because wave energy may be propagated and reflected from various surfaces. There is also the possibility of an oscillation that is a harmonic of the basic wave. Two important points in cavity resonators are (1) how oscillations are forced and (2) how energy is removed. They will effect the mode of operation.

The r-f energy may be introduced to or removed from the resonant cavity, inductively, capacitively, or by radiation.

The energy is in the electrostatic field at one instant and in the magnetic field an instant later, oscillating from one field to the other at the frequency of the applied energy.

In referring to cavity resonators the idea that a conductor is always an "equipotential surface" is untrue; voltages and currents reverse themselves in a space measured in centimeters. An *electrostatic field* can terminate only on electrical charge, hence there must be appropriate distribution of charge on the surface. A *magnetic field* can cease suddenly only on a surface carrying current, hence there must be current flowing in the inside surface of the resonator (only penetrates a very thin skin of the metal surface and cannot be detected on the outside of the resonator).

A general statement, for simple resonators, can be made that it is necessary to have a dimension of an electrical half wave or multiples of a half wave since the electrostatic field is a maximum at the center and minimum at the sides of a simple resonator, otherwise the electrostatic field would be shorted out. (Refer to the data covering a section of wave guide used as a tuned circuit.)

Resonant Frequency "Q" and "Ro"

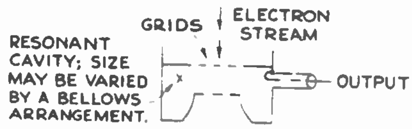
The resonant frequency can be calculated from the shape of the cavity for very simple types of resonators possessing symmetry.

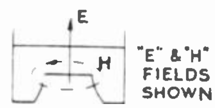
The "Q" can be determined through knowledge of the rate at which energy is lost. A large "Q" may be obtained when the ratio of volume to surface is large. Approximate values of "Q" may be 28,000, 31,000 and 26,000, for a cube, cylinder, and sphere, respectively, when not loaded.

High "Q" does not necessarily imply high shunt resistance ("Ro") in a resonant cavity.

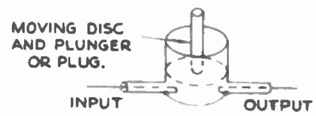
Forms of Actual Cavity Resonators

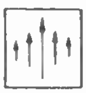
Cavity resonators may take various shapes such as, cube, sphere, cylinder, sphere dimpled on top and bottom, cylinder "dented" at one end (with ends forming grids as in an HF tube, for instance), etc.

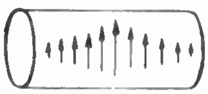




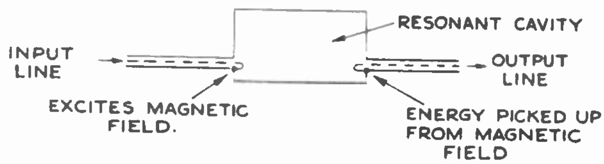
Several possible types of cavity resonators are shown below. The electrostatic lines of force are shown for one possible mode of operation:



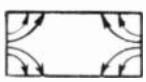

CUBE

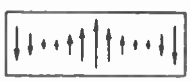

CYLINDER


SPHERE




DIMPLED SPHERE

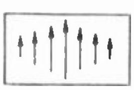

RECTANGULAR

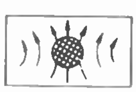

RECTANGULAR

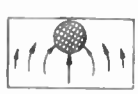
The cavity (box) cannot resonate if it is too small for the wavelength concerned. If the r-f energy is the correct frequency for the cavity, high amplitude centimeter waves (fields) will propagate across and from top to bottom of the cavity.

Tuning Slugs for Cavity Resonators

For the purposes of explanation, a metal sphere is shown in a rectangular resonant cavity, with the "E" lines of force for this particular operation as shown below:


BEFORE


AFTER


AFTER

(1) The slug shortens electrostatic (E) lines of force, hence the capacity is said to *increase.*

(2) The magnetic (H) lines of force are normally weak at the center and are not appreciably affected.

(3) The wavelength *increases* (frequency lower).

If the slug is inserted at one side or the other, the result is as follows:

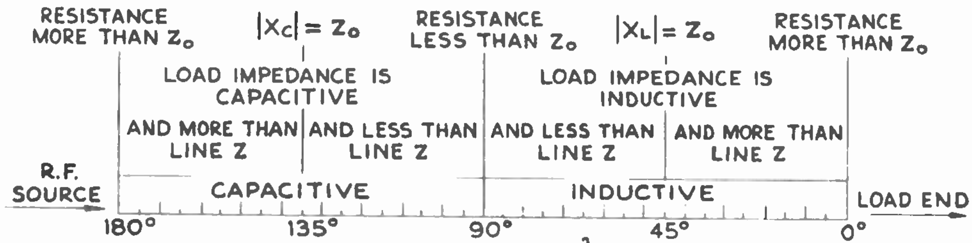
(1) The slug shortens the magnetic lines of force (H), hence the effective inductance is said to *decrease.*

(2) The electrostatic lines of force (E) are normally weak at the side and are not appreciably affected.

(3) The wavelength *decreases* (frequency higher).

Since the two positions of the slug, namely, in the maximum (E) field, and maximum (H) field, change the resonant frequency in opposite directions, it would be expected that a position where no change in wavelength would result might be found.

Appendix on Use of Slotted Line



SCALE LENGTH = $\lambda/2$

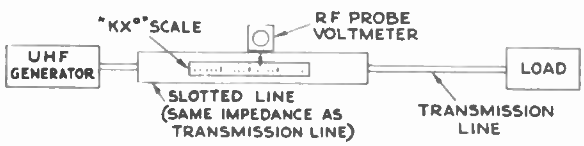
MAKE SCALE LENGTH = ½ WAVE LENGTH AT OPERATING FREQ.

$$\frac{1}{2} \text{ WAVE IN INCHES} = \frac{5908}{\text{FREQ. IN MC}}$$

(This length is based on the use of an air-dielectric slotted line with velocity constant practically the same as air.)

By making a few simple measurements on the slotted line (at the desired frequency) it is possible, with the aid of the charts at the end of this booklet, to determine the impedance and phase angle of any load.

The equipment is set-up as shown:



The procedure is as follows:

1. ***Make a scale*** as shown at top of page.
2. ***Locate a "reference point"*** as follows:
   - (a) Short circuit the far end of the transmission line, at the load. The short circuit must be as direct and effective as possible for accurate results.
   - (b) Adjust the generator for correct frequency. Move the probe to a voltage max. point, and adjust generator output for exactly full-scale reading on probe voltmeter.
   - (c) Move the probe along the slotted line and note the position of min. voltage points. Select a min. near the center of the slotted line and locate this point accurately. This min. will be referred to as the "reference point."
3. ***Fasten the prepared scale*** underneath the probe pointer so the 90 degree mark is at the "reference point."
4. Remove the short circuit.
5. Check and if necessary readjust the generator for correct frequency.
6. Move the probe along the scale and accurately locate the point of min. voltage. The reading in degrees on the scale at this min. voltage point is referred to as "KX°."
7. Note the voltmeter reading at the min. voltage point. Determine the ratio of $\frac{\text{min. voltage}}{\text{max. voltage}}$ This is the standing-wave ratio, referred to as "R." (If the rectifier in the r-f voltmeter is non-linear, the ratio may be corrected as described previously.)

Having determined values of "KX°" and "R," it is then necessary to use the correct chart to determine the impedance and phase angle of the load.

There are four charts included in this booklet.

Use #1 if KX° is between 0 and 45°, or 135° and 180°.

Use #2 if KX° is between 45° and 135°.

(Charts #3 and #4 are enlargements of #1 and #2, respectively, for greater accuracy when the standing-wave ratio is between 0.7 and 1.0.)

As an example, if—

R, the standing wave ratio, $\frac{\text{Min. voltage}}{\text{Max. voltage}} = 0.5$

KX°, $= 60°$

Zc, the line impedance, $= 40$ ohms

As KX° is 60°, use chart #2.

Locate R = 0.5 on top of #2 chart and follow this line around until it crosses the KX = 60° line. Mark this point and from it go straight across the chart to find that the ratio of the

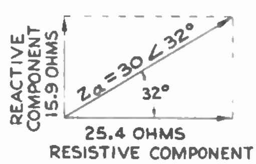
$$\frac{\text{load impedance}}{\text{line impedance}} = 0.75$$

As the line impedance is 40 ohms, the load impedance is 40 x 0.75 or 30 ohms.

From the marked point (where R crosses KX°), drop straight down and note that the angle of the load is 32° (inductive).

The load impedance (Za) may be expressed in terms of resistive and reactive components:

$$Za = 30 \cos 32° + J\,30 \sin 32°$$
$$= 25.4 + J15.9 \text{ ohms.}$$



EXPRESSED VECTORIALLY

Position of Standing Waves for Various Loads

With the load *short circuited,* any convenient point of *minimum voltage* on the slotted line may be used as the *"reference point."*

To determine KX° by the position of voltage maximum, place the scale so 0° is at a reference point, as shown at top of following chart.

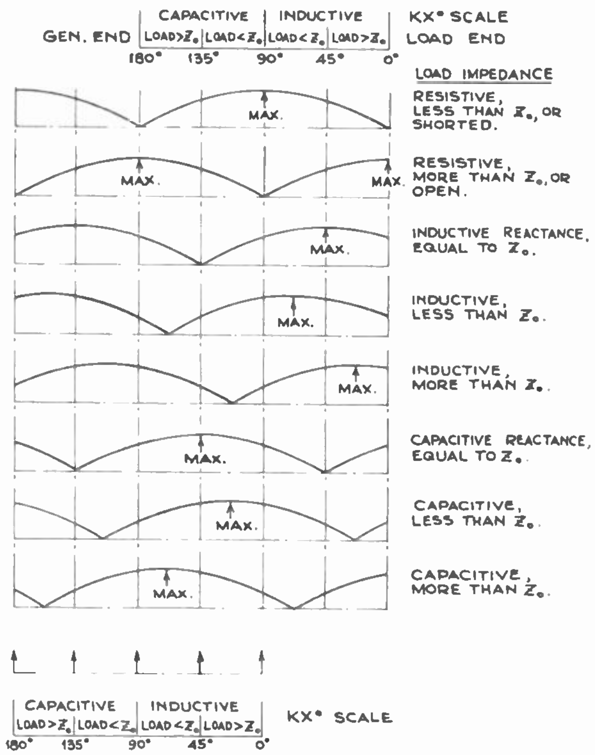
To determine KX° by the position of voltage minimum, place the scale so 90° is at a reference point, as shown at bottom.

The answer is the same in either case.

Owing to the "sharper" indication, it is generally preferable to use a minimum voltage point to determine KX°. However, when using a relatively low frequency, a half-wavelength may be longer than the slotted line and the minimum voltage points may fall beyond the ends of the slotted line. In such cases, it is possible to use a maximum voltage point in determining KX°.

The procedure is to short circuit the load and locate the minimum voltage point nearest the load end of the slotted line. Use this as the "reference point." (If the minimum voltage reference point is not close to the load end of the slotted line, change the length of the transmission line so that the minimum voltage reference point is near the load end of the slotted line. Place the prepared scale (shown in previous sketch) so that the *zero-degree mark is at the reference point.*

Remove the short-circuit and locate the first maximum voltage point from the reference mark (on generator side of reference mark). The reading on the degree scale at this maximum voltage point is KX°.



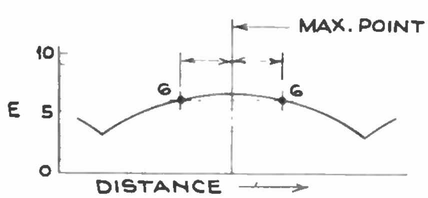
Load Connected Directly at End of Slotted Line

In some applications, the load is connected directly to the end of the slotted line, without using a transmission line. In this case the question of using the minimum or maximum voltage point in determining KX° again depends on the required operating frequency and the length of the slotted line.

With relatively high frequencies, use the first procedure (in which a voltage minimum is used in determining KX°).

With relatively low frequencies, use the point where the load is connected to the slotted line as the "reference point." Place the scale so the zero degree mark is at this reference point. The first maximum voltage point, from the reference point, is KX°.

Note on Obtaining Maximum Voltage Point



As an aid in obtaining accurate location of maximum voltage points, it is suggested that two voltage points of equal magnitude be selected, one on each side of the maximum point, then choose the distance half way between these two points as the maximum point. This same system may be used to determine the location of *minimum* voltage points.

Charts for Use with Slotted Line

Z_C = CHARACTERISTIC IMPEDANCE (SURGE IMP.) OF CONCENTRIC TRANSMISSION LINE OR PARALLEL WIRE LINE.

Z_a = MAGNITUDE OF LOAD IMPEDANCE (TERM IMP.) AT END OF TRANSMISSION LINE

θ_a = ANGLE OF LOAD IMPEDANCE

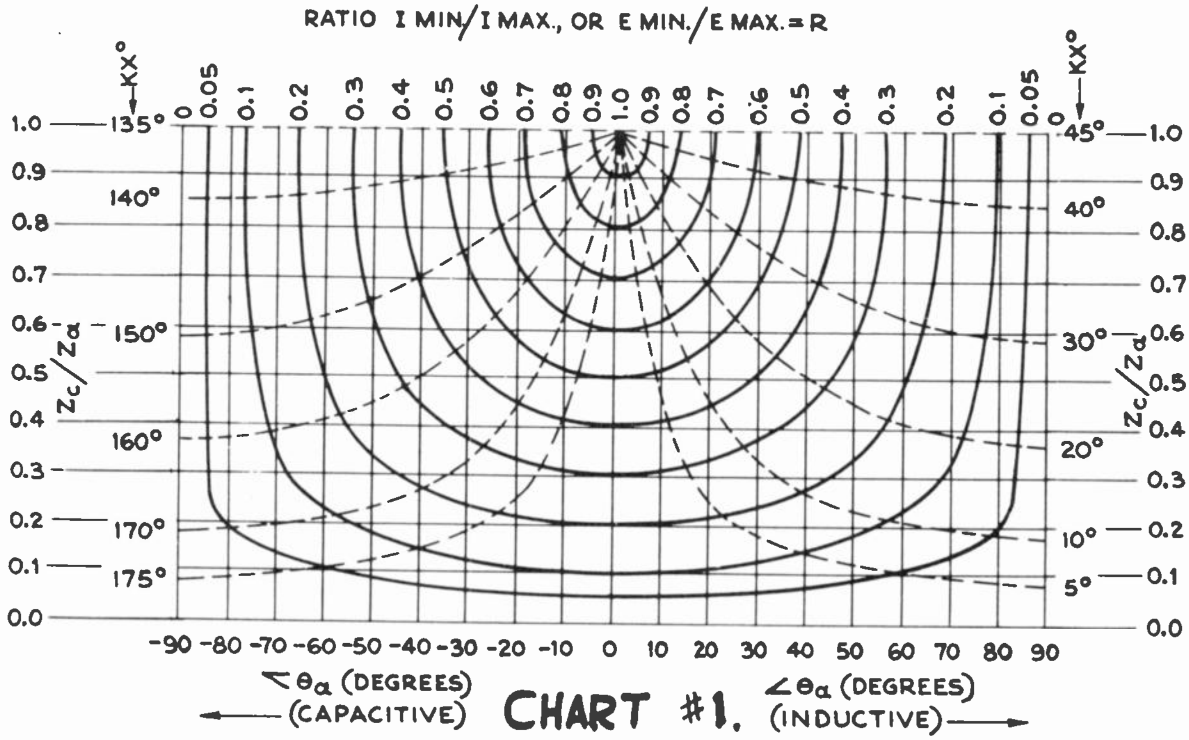


CHART #1.

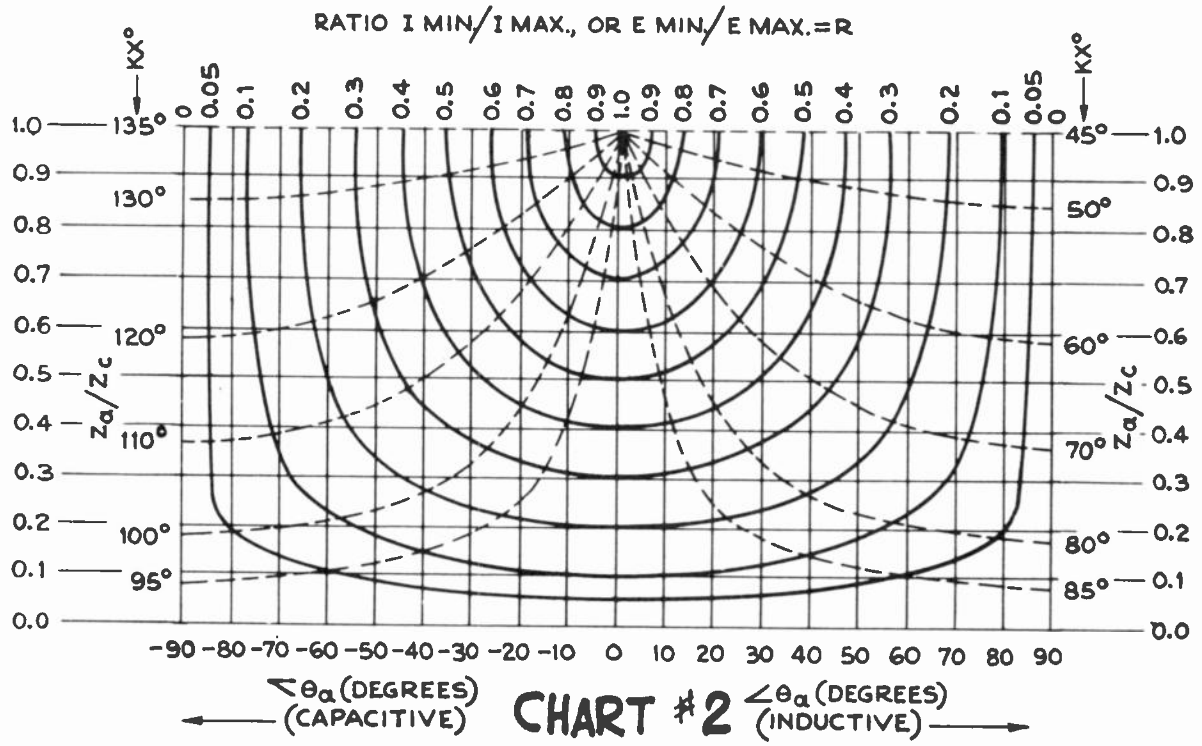


CHART #2

Charts for Use with Slotted Line

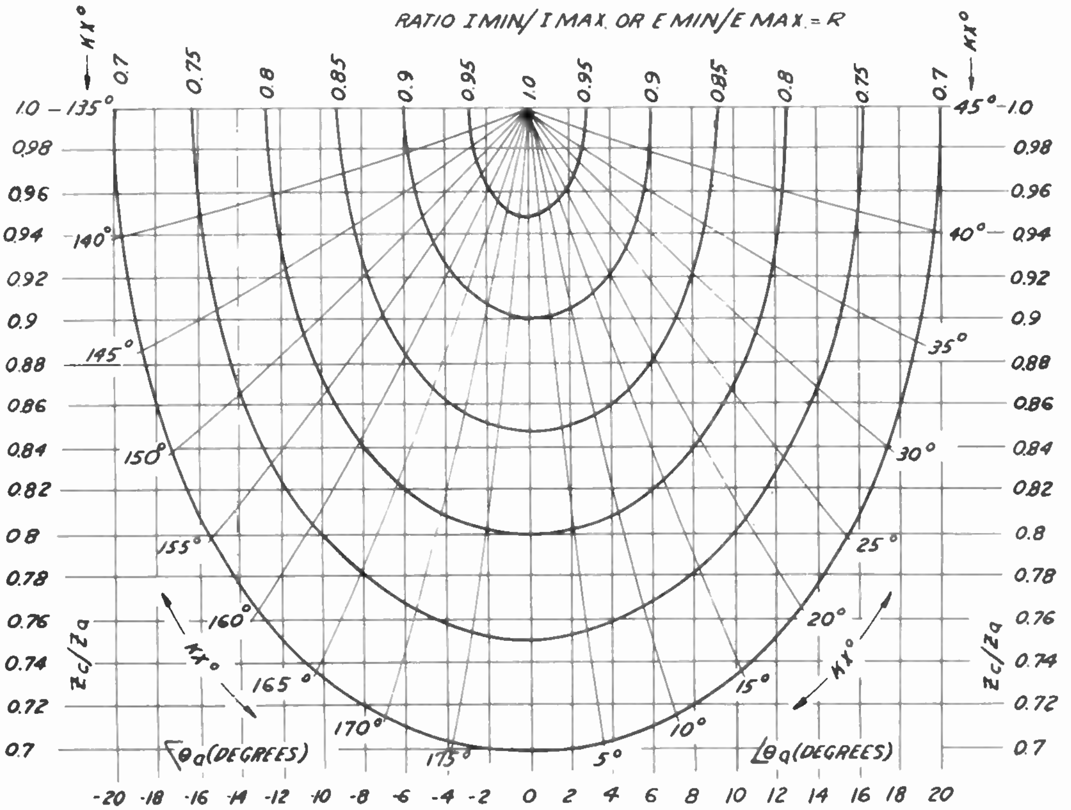


CHART Nº 3 - ENLARGEMENT OF PART OF CHART Nº 1

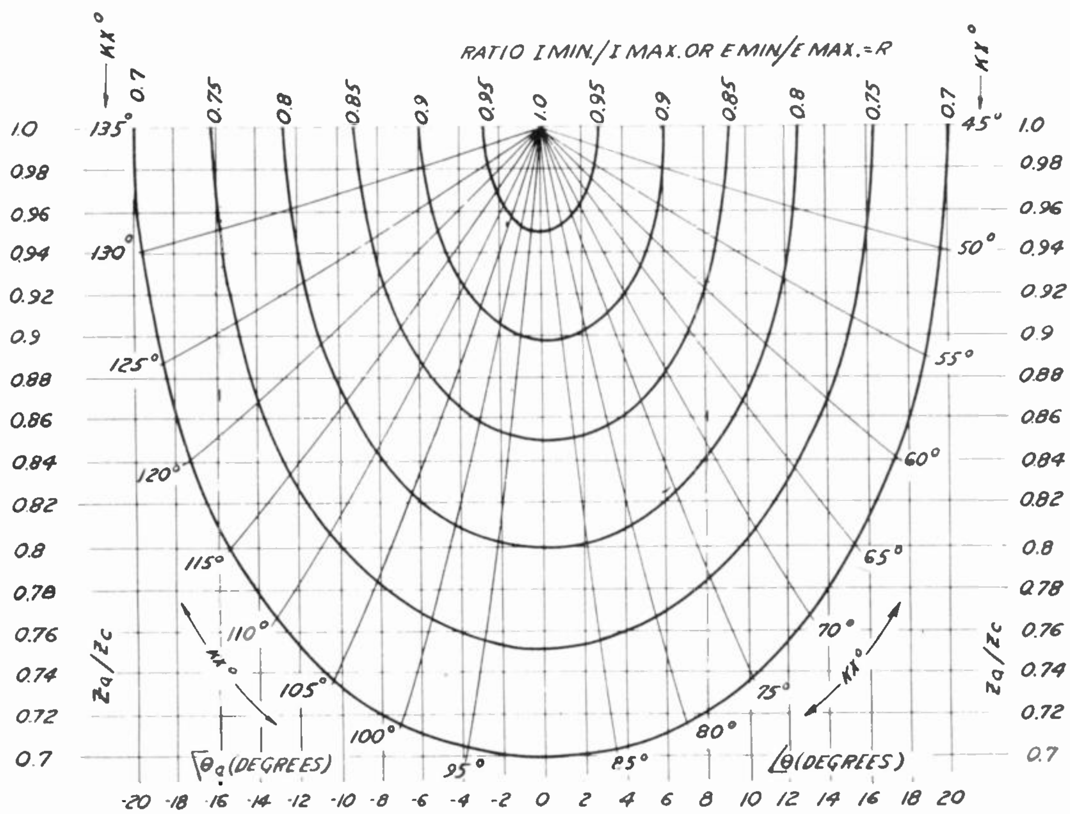
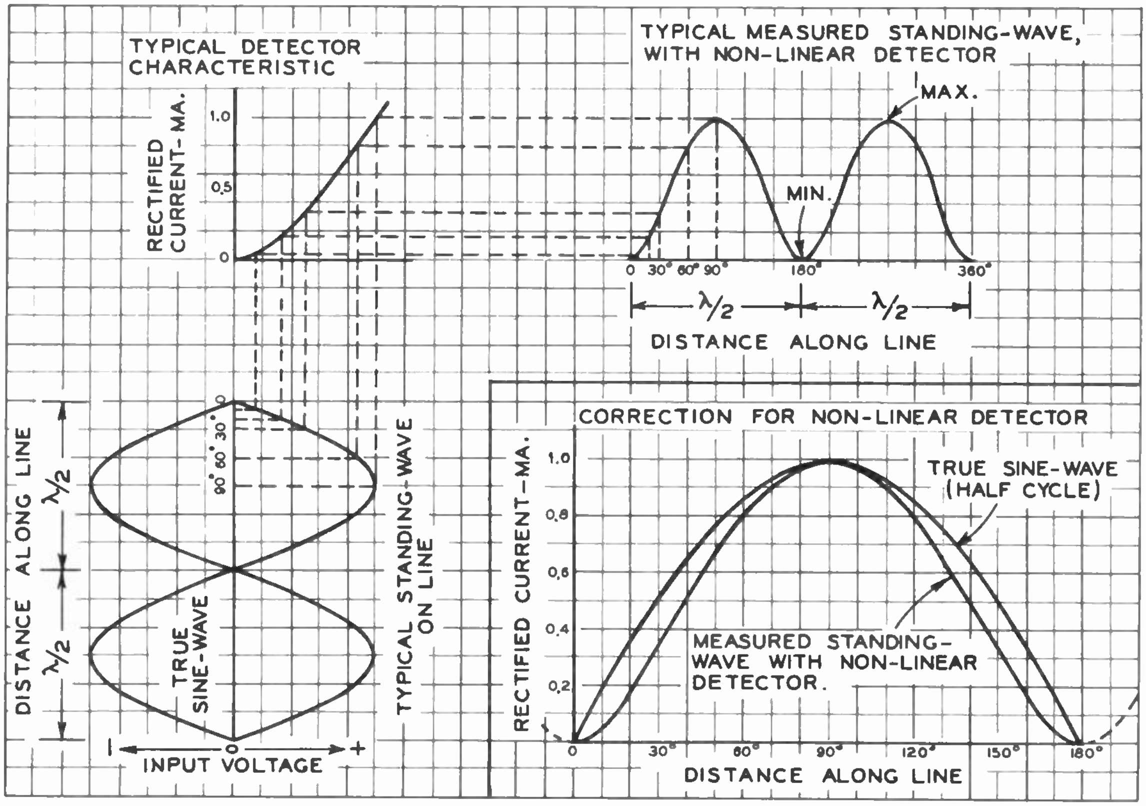


CHART Nº 4 - ENLARGEMENT OF PART OF CHART Nº 2

Effect of Non-Linear Detector



Ratio of Power Loss in Unmatched Line