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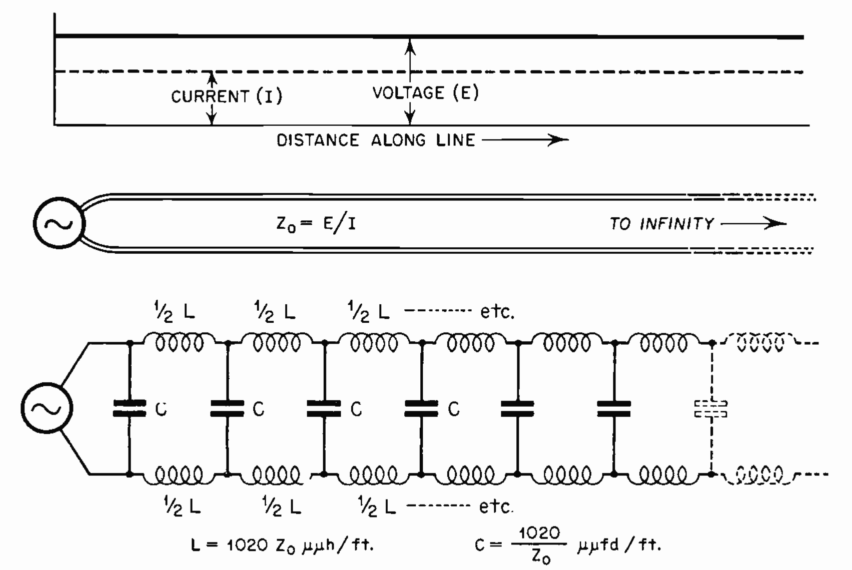
R. F. Transmission Lines

By the Engineering Department, Aerovox Corporation

With the increasing utilization of the high-frequency portion of the radio frequency spectrum, transmission lines are assuming greater importance for both the transmission of energy and as circuit elements. Special transmission line sections are used extensively as resonant circuits in place of lumped-constant, coil-and-condenser circuits in many VHF and UHF applications. The cavity and waveguide circuits used at microwave frequencies can also be shown to be evolved from the types of transmission lines employed at lower frequencies and are subject to similar laws.



INFINITE TRANSMISSION LINE AND LUMPED EQUIVALENT

FIG. 1

In the past, a thorough knowledge of transmission line theory was used to great advantage only by those engaged in antenna or transmission line work. Now, however, with coaxial and open-wire line sections being used as circuit elements in the transmitters and receivers themselves, a basic understanding of their functioning is required of every worker in the field, and merits frequent review.

Fundamental Line Properties

A transmission line is an electrical system, usually consisting of two metallic conductors, which is used to transfer electromagnetic energy from one point to another. Any line of this type, whether it be coaxial, open-wire, waveguide, or any of the other possible configurations, is characterized by an attenuation constant, a velocity factor, and a characteristic or "surge" impedance. These properties are determined by the geo-

To All Aerovox Research Worker Subscribers: The January 1951, issue of the AEROVOX RESEARCH WORKER featured an article concerning the construction of a TV Field Strength Meter wherein we specified the use of an RK 62 or RK 61 gas-filled tube. Military and government requirements have caused these tubes to become difficult to obtain. A substitute will be recommended in the April Issue of the AEROVOX RESEARCH WORKER. THE EDITORS.

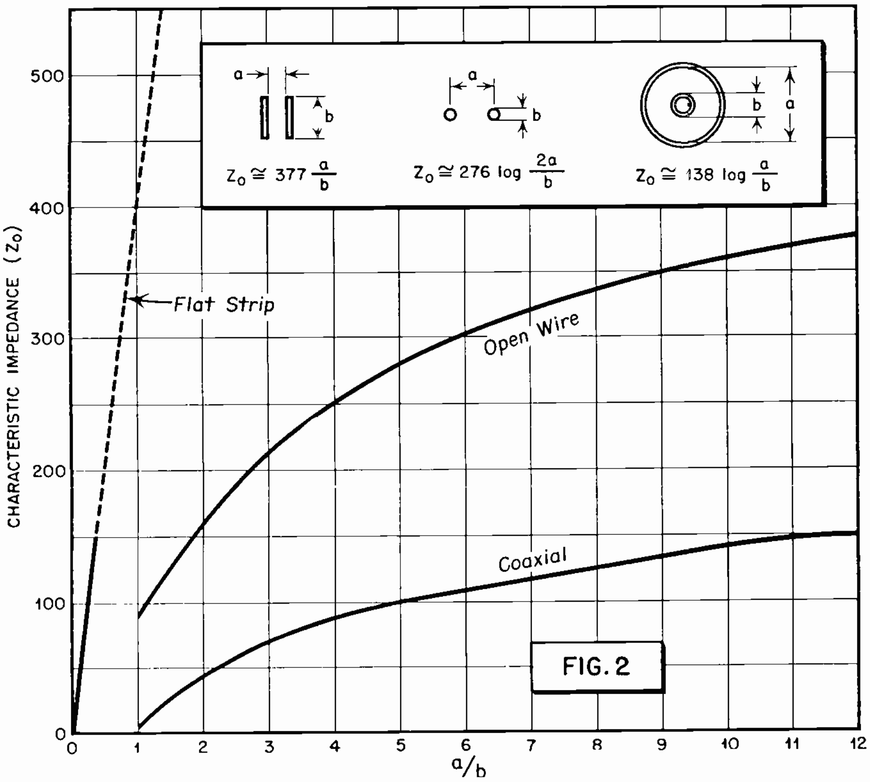


FIG. 2

metry of the conductors forming the system, the materials of which they are made, and the dielectric material used as insulation between them.

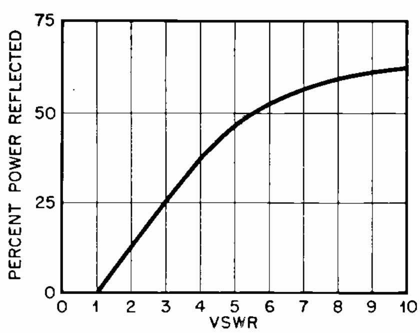
Losses in a r.f. transmission line are of three types; heat losses in the metallic conductors, losses in the dielectric material surrounding the conductors, and losses occasioned by radiation of energy from the line into surrounding space. The latter losses are of importance only in unshielded types of lines. Although the attenuation constant is most properly expressed in *nepers* per unit length, *decibels* per unit length is more frequently used in practice. These units are obtained by multiplying the attenuation constant in nepers by 8.69.

The *velocity factor* of a transmission line is defined as the ratio of the velocity of an electromagnetic wave traveling on the line to the velocity of a wave of the same frequency traveling in free space. This characteristic is controlled principally by the dielectric constant of the material used between the line conductors. It is unity for common lines having air dielectric, since waves on such lines travel with the speed of light as they do in free space. Lines having solid dielectric material between the conductors have velocity factors less than unity. As an example, the velocity constant of 300 ohm television twin-lead is about .82. The velocity factor is of importance since it defines the length of waves on the transmission line and must be considered when cutting resonant sections for antennas, matching sections, or other purposes. In the example mentioned above, the wavelength on the line is 82% of the length of a wave of the same frequency in free space. In other words;

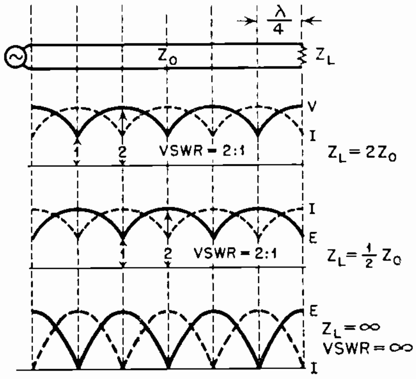
(1) $$\text{VELOCITY FACTOR } (\beta) = \frac{v}{c} = \frac{\lambda'}{\lambda}$$

Where:
v is the velocity of a wave on the line.
c " " " " " " in space.
λ' is the length of a wave on the line.
λ " " " " " " in space.

The concepts of characteristic impedance and impedance matching are probably the most important in the use of transmission lines. These ideas are universally employed to insure maximum transfer of energy from one point to another by means



PLOT OF POWER REFLECTED vs. VSWR
FIG. 4



EFFECT OF TRANSMISSION LINE TERMINATION ON S.W.R.
FIG. 3

of transmission lines.

The characteristic impedance of a transmission line may be defined as the ratio of voltage to current on the line if it is infinitely long or is otherwise arranged so that waves travel on one direction only. Under this condition, current and voltage distribution is uniform with distance along the line and it is said to be "flat". Fig. 1 shows a distribution of this kind on a hypothetical infinite line. The lumped-constant equivalent of the line is also shown. The coils represent the inductance of the conductors and the capacitances are formed by the proximity of the conductors to each other. If the inductance and capacitance values per unit length of the line are known, the characteristic impedance is expressed approximately as:

(2) $$Z_0 = \sqrt{\frac{L}{C}} \text{ ohms}$$

In Fig. 2 the characteristic impedance of several commonly used types of air-insulated transmission lines are plotted.

Impedance Matching

Infinitely long transmission lines are, of course, only possible in theory. In practice, other means must be employed to prevent waves from being reflected from the far end of the line and causing *standing waves,* with attendant loss of efficiency. This is usually accomplished by terminating the line with a load impedance which is a pure resistance equal to its characteristic impedance. Under these conditions, all energy reaching the load will be absorbed and no reflections will result. Voltage and current are then uniformly distributed along the line as in Fig. 1, and the line is said to be "matched".

If the transmission line is *not* terminated in a resistive load impedance equal to its characteristic impedance

(Zo), reflections will occur from the load end due to unabsorbed energy traveling backward toward the generator. These reflected waves are out of phase with the incident waves at some points and in phase with them at others, so that the oppositely traveling waves alternately add or subtract. The result is a system of stationary standing waves. Fig. 3 shows the standing wave and phase conditions for lines terminated in various manners. The amplitude of the voltage standing wave pattern is proportional to the ratio of the terminating resistance to the characteristic impedance of the line, or vice versa, whichever is greater than unity. Thus, a 300 ohm line terminated by either a 100 ohm or a 900 ohm resistive load will show a voltage standing wave ratio (VSWR) of 3:1. In a similar manner, a length of transmission line shorted at the end will exhibit the same (theoretically infinite) VSWR as one left open circuited at the load end. The standing wave ratio thus serves as a convenient measure of the degree of match existing between the line and its load. The percentage of power lost due to reflections from a miss-matched load, plotted versus VSWR is given in Fig. 4.

Line Sections As Circuit Elements

Special transmission line sections are used for resonant circuits, impedance transformers, filters and r.f. chokes in high frequency and microwave practice. At least a qualitative understanding of the properties of such line sections is necessary for a grasp of modern r.f. circuitry.

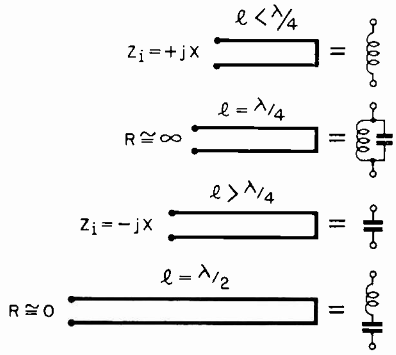
Most of the special applications of short sections of transmission lines are based on the properties of a uniform line shorted at the load end. The input impedance (Z_i) of such a line, if losses are neglected, is expressed as:

$$Z_i = Z_o \tan 2\pi \frac{\ell}{\lambda} \qquad (3)$$

Where:

Z_o is the line impedance.
ℓ is the line length in cm.
λ is the operating wavelength in cm.
2π is 6.28 radians or 360 degrees.

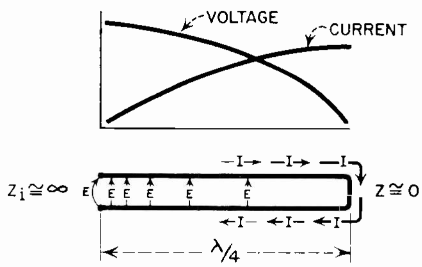
An inspection of this equation indicates that the input impedance of the shorted line section varies as the tangent of its electrical length in radians and is infinite for a line of one-quarter wavelength or odd multiples of quarter-wavelengths long. In practical cases, when losses are present, the input impedance is not infinite but is very high and is a pure resistance. For sections which are *even* multiples of quarter-wavelengths long,



CHARACTERISTICS OF SHORTED LINE SECTIONS
FIG. 5

the input impedance is very low (theoretically zero) and is also resistive. Thus, a quarter-wavelength section is equivalent to a parallel resonant circuit at its input terminals, while a half-wavelength section shorted at the end has the characteristics of a series resonant circuit. Intermediate lengths are reactive and have the properties of coils and condensers. These comparisons are illustrated in Fig. 5.

By far the most important transmission line "building block" used at VHF and UHF to form circuit elements is the quarter-wave shorted line. It recurs so frequently in so many forms that it warrants special attention.



VOLTAGE AND CURRENT ON ¼ WAVE LINE
FIG. 6

Fig. 6 shows the voltage and current distribution on a line section of this type. The voltage is maximum across the open end where the impedance is high and drops to effectively zero at the short where the impedance is low. The current is maximum through the short-circuited section and drops to a very low value at the open end.

The characteristics of the quarter-wave resonant line shown in Fig. 6 are useful in helping to visualize the properties of the specialized circuits used at elevated frequencies. Cavity and coaxial resonators, as well as waveguides, may be thought of as

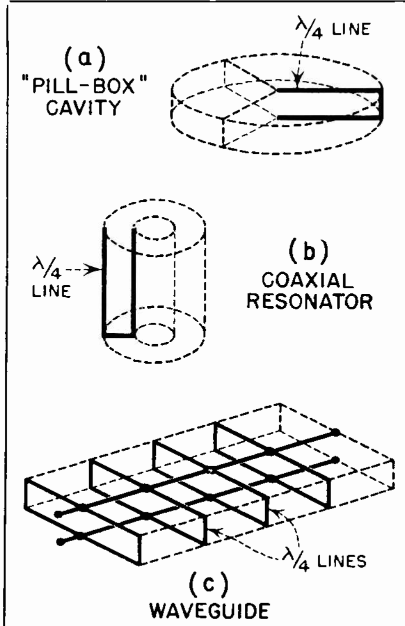


FIG. 7

being evolved by connecting large numbers of quarter-wave open line sections in parallel in various manners to form self-shielded circuits. Such arrangments have much higher "Q" factors than conventional coil-and-condenser circuits because radiation losses are prevented. Fig. 7 illustrates the development of these special circuits from the simple resonator of Fig. 6.

The formation of a "pill-box" cavity resonator is shown in 7 (a). Since the input impedance of the quarter-wave line (shown as a solid line) is very high, a large number of such lines may be connected in parallel without prohibitively lowering the impedance at the terminals. If enough such elementry resonant sections are connected in this manner to form a solid figure, the result is a resonant structure having a frequency *nearly* equal to the frequency of each of the line sections forming it. All r.f. fields are confined within the metal "can". In a similar manner, the coaxial resonator (Fig. 7b) is formed. The open end is usually closed to prevent radiation losses.

A simple concept of the evolution of a waveguide is depicted in Fig. 7c. Here a parallel wire line is supported by "metallic insulators" consisting of quarter-wavelength line sections connected across it. At the frequency at which these sections are resonant, they have little effect on wave propagation down the line since their shunting impedance is very high. If enough of these supports are added, all fields are confined within the guide.

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