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PART 2. WAVE GUIDES

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Two-wire transmission lines and coaxial (concentric) lines and cables have found wide acceptance in communications and research for conveying high-frequency energy between points in an electrical system. These conducting systems, and refined adaptations of them, have been employed at frequencies up to several hundred megacycles with reasonable success. Both two-wire lines and concentric sections have been used also as tank circuit elements in high-frequency oscillators and amplifiers and as the tuned portion of wavemeters. The latter-mentioned systems have been practicable at ultra-high frequencies because the short wavelengths involved have permitted fractional-wavelength elements with small physical dimensions. Such systems would have been just as useful at lower communication frequencies but the required dimensions would have been ungainly. (For example; a quarter-wave section of 2-wire transmission line is only about 29.5 inches long at 100 Mc., while a similar section at 1000 kc. is approximately 24.5 feet long).

At the extremely high frequencies encountered in microwave work, the *wave guide* has taken precedence over the two-wire transmission line and the coaxial cable.

DESCRIPTION

A wave guide is a *pipe* through which microwave energy may be transmitted. The wave guide differs from the concentric line principally in that it has neither central conductor nor return circuit, but only an outer wall. Pipes used most frequently as wave guides are circular, oval, or rectangular in cross section, although the latter form appears to have the widest application at this writing. Complex cross sections distinguish several types of wave guides that have been employed experimentally and in service, and in some composite forms the configuration alters the electrical characteristics at various points along the pipe.

Some types have made use of low-loss solid dielectric filling, but most wave guides are hollow. The conventional wave guide is metallic, although somewhat less satisfactory propagation has been obtained experimentally at certain frequencies through solid dielectric rods employed as wave guides. The wall thickness of the pipe is not usually a material factor. Microwave energy may be transmitted through wave guides with such improved efficiency as to justify abandonment of lines and cables at those very high frequencies where wave guide dimensions are small enough to be practical.

The hollow, rectangular wave guide may be considered to have been evolved from a two-wire transmission line

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on each side of which have been connected facing quarter-wave shorted stubs. This evolution is depicted by Figure 1.

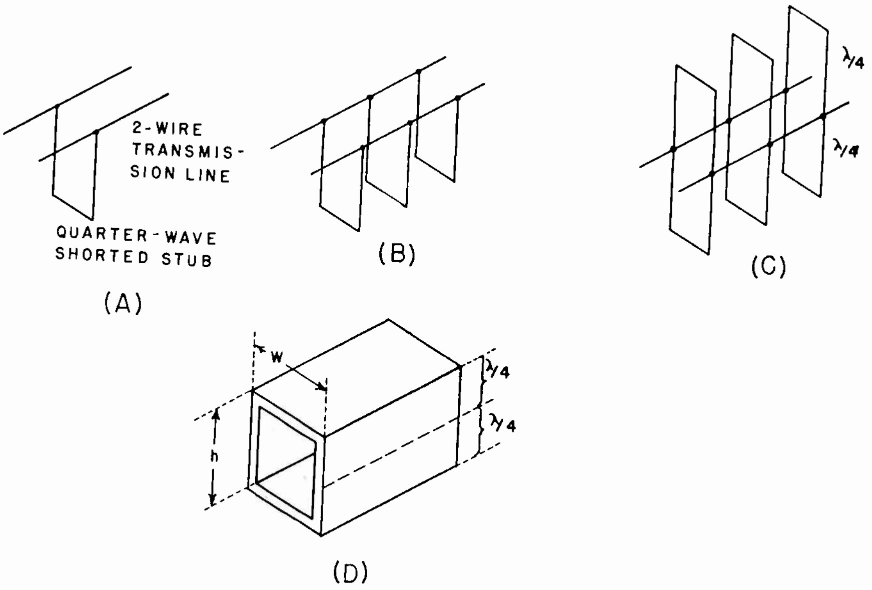

Figure 1

At 1-A, a two-wire transmission line is shown with one shorted quarter-wave stub connected below. The nature of energy distribution along the shorted quarter-wave stub is such that the open end of the stub is equivalent to a *high impedance*. In consequence, the line impedance is not disturbed appreciably by connection of the stub. A number of similar stubs may be hung on the line, as shown at 1-B, also without altering the line impedance detrimentally. And, continuing the process still further, facing quarter-wave stubs may be connected above the line as well, as shown at 1-C, with an upper stub matching every lower one. The addition of facing stubs above and below the line may be carried out indefinitely, the spacing between adjacent stubs becoming successively smaller until finally the adjacent stubs are in close contact with each other. An infinite number of such stubs thus finally constitutes a rectangular pipe open at each end, as shown at 1-D. In the latter illustration, the dashed lines represent the position formerly occupied by the transmission line. This evolution establishes the theoretical minimum height which this type of wave guide may have as ½ wavelength. Other versions may be some multiple of a half-wavelength in height. However, the minimum height (h) which this type of pipe may have is ½ wavelength. The width (w) serves to establish the voltage breakdown and *mode of operation*. Mode will be described in its place.

From the foregoing description, it may be seen that the tube or pipe comprising a simple rectangular wave guide shows little complexity on the surface. It is not so simple, however, to gain an exact understanding of propagation of microwave energy through even a simple wave guide, since a complete examination of the action requires application of Maxwell's equations. Nevertheless, it is possible for the reader having no command of higher mathematics to gain a practical understanding of wave guide action in terms of physical phenomena with which he already has some acquaintance. The following paragraphs aim to present such a qualitative picture.

PROPAGATION THROUGH RECTANGULAR WAVE GUIDE

Slater has stated in his textbook *Microwave Transmission that* "an infinitely long hollow pipe, of rectangular cross section and conducting walls, transmits many types of electromagnetic waves with small attenuation and is a practical transmission line."

Microwave energy introduced at one end of a wave guide will tend to pass through the guide in a manner analagous to the behavior of high-frequency electromagnetic waves transmitted into space. That is; the electromagnetic waves will, if the wave guide is properly proportioned for the operating frequency and the energy is properly introduced (as will be shown later), be reflected from wall to wall in a zig-zag passage through the guide. Propagation of this sort, illustrated by Figure 2, resembles that of the sky-wave component of short waves radiated from an antenna. Each wave comprises an electric (E) and a magnetic (H) component operating at 90° with respect to each other but in time phase.

With highly conducting inner walls, which are assumed, the angle of incidence of the waves is equal to the angle of reflection. At each reflection, the electric field of the wave is reversed. This reversal is depicted in Figure 4 by a change from a solid to a dashed line after each indicated reflection.

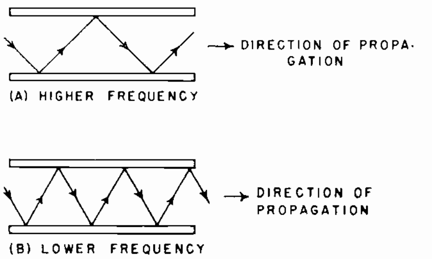

FIG. 2

In a wave guide of given dimensions, high-frequency waves (See Figure 2-A) will undergo less reflections between walls than will waves of lower frequency (Figure 2-B). This gives the higher frequency the more rapid propagation through the wave guide. The velocity of propagation of a wave of any frequency through a wave guide (termed *group velocity*) is lower than the velocity of a wave of the same frequency in air because of the zig-zag path taken inside the guide. Multiple reflections cause the wave to travel farther while in the guide than the actual guide length. In a simple rectangular wave guide, group velocity depends upon dimension h (See Figure 1) and is directly proportional to frequency.

Operation of the wave guide differs especially from that of the simple 2-wire transmission line in that reflections in the former are not in the direction of propagation but at an angle. These "angular reflections" give rise to standing waves in the usual manner. In order to comprehend, in a physical sense, the formation of standing waves within a wave guide, it is helpful to consider that the electric field of the wave is reversed at each reflection. The reflected component accordingly is of opposite phase, and cancels the ordinary or primary component. The physical concepts are the same that would apply to the simple 2-wire transmission line in which the transmitted wave encounters reflections from the far end of the line and the result is the setting up of maxima and nodes along the line.

In order to achieve good wave guide operation, as just explained, any skin currents flowing on the metallic walls of the guide must be negligible if not completely zero. This requirement necessitates that the electric field of a wave to be transmitted be minimum, or zero, where it meets the walls. Figure 3 shows how this is accomplished by proper dimensioning of the guide for a given operating frequency. The arrangement depicted will insure that the electric field will be tangent to the guide wall surface and zero at every point.

Both 3-A and 3-B show distribution of the electric field intensity within the guide. The corresponding sine curves are plots of field intensity, with positions in space as the ordinates. Close grouping of arrows corresponds to high field intensities, and vice versa. Those portions of the field which have not been included within the guide (and which do not exist outside of the guide but are shown here merely for reference) are indicated in Figure 3-A by outside arrows. In Figure 3-A it is seen that the electric field has the required zero intensity at each wall. In order for this condition to obtain, exactly one-half wavelength is represented by the space distribution of the field intensity within the guide. And it may be seen by examination of the arrow grouping and the corresponding sine plot that no smaller fraction of a wavelength would place electric field minima at the walls. However, a *multiple* of ½ wavelength might place zero field intensity points at the walls of a wave guide of the same size. This is shown in Figure 3-B where three half-waves have been "fitted" into the same guide dimension.

These illustrations give explanation and justification regarding the minimum size of ½ wavelength for the dimension h. The w dimension, as mentioned earlier in the article, is not particularly critical. The fact that multiples of ½ wavelength will be propagated through the wave guide to the exclusion of submultiples makes a wave guide comparable to a high-pass filter. Thus, a wave guide of given dimensions has a definite cut-off or *critical* frequency. In Figure 2-A, the wave frequency is somewhat higher than the cut-off frequency, while in 2-B the wave frequency is at or near cut-off. In connection with discussion of these facts it is interesting to note, however, that in practical operation the frequency-determining dimension of the wave guide is limited to slightly more than an exact half-wavelength.

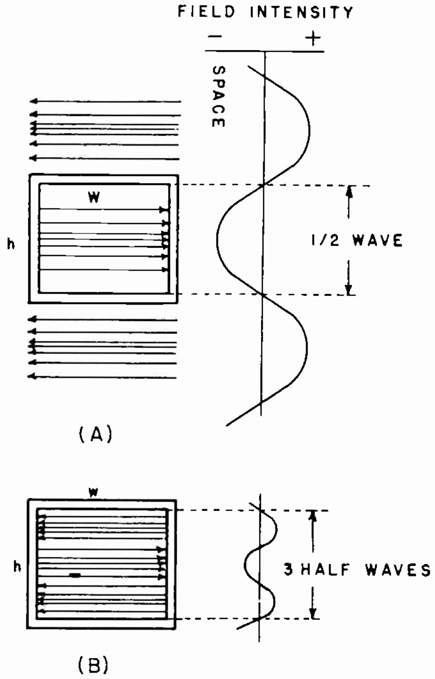

FIG. 3

It must not be overlooked that both electric and magnetic fields are present in the wave guide and that these two fields act at right angles to each other. Both are reflected by the walls of the wave guide. When there is an equal number of reflections of each field, all at the same angle, the two fields do not overlap at any point, and maximum energy is transmitted through the guide. Since a number of frequencies higher than the critical may be transmitted by a given wave guide, the condition just described for maximum transfer obviously does not exist for each of them. In order to obtain maximum transfer, the proper guide dimensions must be employed for a specific operating frequency.

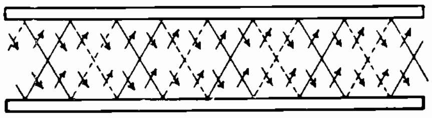

FIG. 4

Figure 4 illustrates the condition just described for maximum propagation. The reversing electric field is depicted by the alternate heavy and dashed lines, while the magnetic field is indicated by the arrows. Points of reflection of the electric field are separated by ½ wavelength, as are also those of the magnetic field. Electric and magnetic reflection points are separater by ¼ wavelength.

Decreasing the angle of incidence results in fewer reflections of the magnetic field of a given wave, but more of the electric field. As the angle is lowered, the direction of the magnetic field path approaches the direction of propagation — that is, the lengthwise axis of the wave guide. At zero degrees, the direction of the magnetic field coincides with the direction of propagation, but no energy is transmitted by the guide because the electric field, being perpendicular to the direction of propagation, then undergoes only a series of reflections back and forth between the walls.

READING LIST,

WAVE GUIDES

Hoag, J. B. *Basic Radio.* 6th Printing. (D. Van Nostrand Co., Inc., New York, N. Y.) pp. 330-334.

King, R. W. P.; Mimno, H. R.; and Wing, A. H. *Transmission Lines, Antennas, and Wave Guides.* 1st Edition. (McGraw-Hill Book Co., Inc., New York, N. Y.) pp. 244-294.

Reference Data for Radio Engineers. (Federal Telephone and Radio Corporation, New York, N. Y.) pp. 118-122.

Skilling, H. H. *Fundamentals of Electric Waves.* (John Wiley & Sons, Inc., New York, N. Y.) pp. 155-182.

Slater, J. C. *Microwave Transmission.* 1st Edition. (McGraw-Hill Book Co., Inc., New York, N. Y.) pp. 124-150.

Terman, F. E. *Radio Engineers' Handbook.* 1st Edition. (McGraw-Hill Book Co., Inc., New York, N. Y.) pp. 251-264.

Practical Analysis of U. H. F. J. R. Meager and H. J. Markley. (RCA Service Co., Inc., Pub.) pp. 14-17.

Radio Amateur's Handbook (American Radio Relay League), 22nd Ed. pp. 55, 56.

Fields and Waves In Modern Radio. Simon Ramo (John Wiley and Sons, Inc.)

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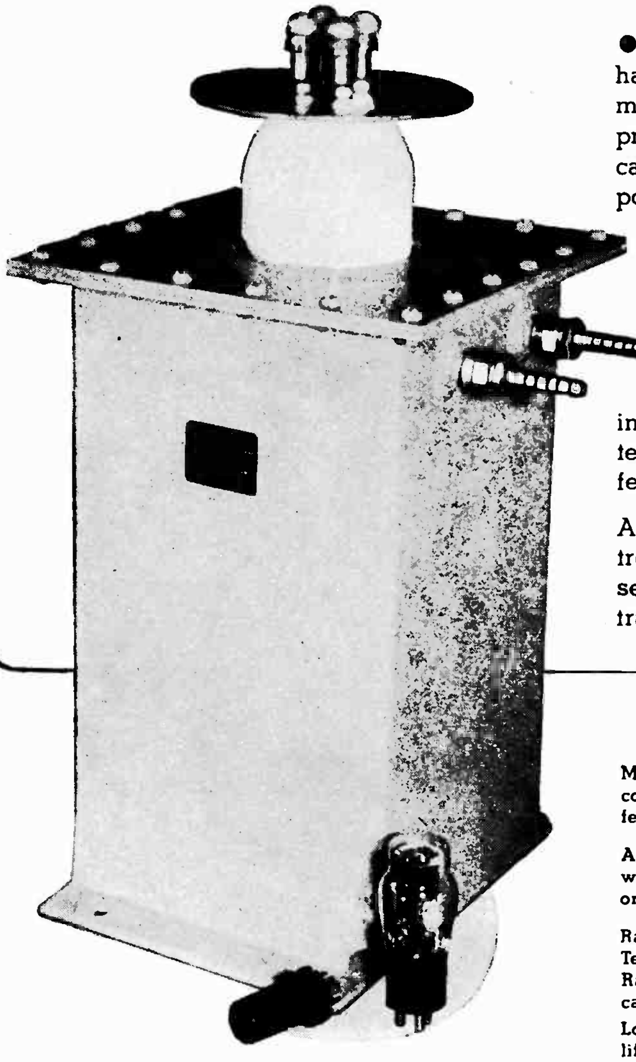

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