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PART 3. WAVE GUIDES

By the Engineering Department, Aerovox Corporation

In Part 2, it was shown that the electric and magnetic fields of a wave, acting at right angles to each other, are both reflected by the guide walls. It was explained also that the angle of incidence is governed by the signal frequency and wave guide dimensions, and that the size of this angle affects the propagation efficiency. From these conditions may be visualized two extremes of operation — one in which the magnetic component is reflected back and forth between the wave guide walls, the electric component being parallel to the direction of propagation; and the other in which the electric component is reflected perpendicularly between the walls, the magnetic component being parallel to the direction of propagation. Maximum propagation efficiency is obtained when the angle of incidence is such that the electric and magnetic components do not overlap at any point within the wave guide. Thus, it is established that wave guide action depends upon the distribution of the fields within the pipe.

MODE OF PROPAGATION

The two fields may be arranged inside the wave guide in a variety of ways. Different arrangements will give rise to different degrees of propagation of each field. If the wave guide is part of an oscillating circuit, the arrangement of the fields likewise will determine the manner of oscillation. Several types of operation accordingly are available with a given wave guide, depending upon electric and magnetic field distributions. These types are referred to as the *modes* of operation (or propagation) of the wave guide.

Modes are grouped into two main categories. One of these, designated *TE*, is characterized by the fact that the magnetic or H field is in the direction of propagation (that is, along the longitudinal axis of the wave guide), while the electric field is transverse. In the case of the other mode, designated *TM*, the electric field has a component in the direction of propagation, while the magnetic field is transverse. The letters TE stands for *transverse electrostatic*, and TM for *transverse magnetic*. TE waves are known also as *H* waves; TM as *E* waves. However, the Wave Guide Committee of the Institute of Radio Engineers has recommended exclusive use of the terms TE and TM. Subscripts placed after the T, E, and M identify closely the numerous modes of operation occurring in the two main groups. For example, the double-subscript notation TE_{01} applies to the mode corresponding to the simple field distribution shown in Figure 1. Here, the electric and magnetic fields have their maxima and minima coincident at the same points in the guide.

When these designations are applied to rectangular wave guides, the first subscript refers to the number of half-period variations of the field along the *w* dimension, or X-axis (See Figure 1), and the second denotes the number of half-period variations along the *h* dimension, or Y-axis. The basic modes for rectangular wave guides are $TE_{0\,1}$ (also termed $H_{0\,1}$), $TE_{1\,1}$ (also termed $H_{1\,1}$), and $TM_{1\,1}$ (also termed $E_{1\,1}$). Distribution of electric and magnetic fields in the latter two modes are shown in Figures 2 and 3, respectively. A variety of high-order modes may exist in addition to the three fundamental ones shown in Figures 1, 2, and 3.

The *dominant mode* for a particular wave guide is the mode with the highest cutoff frequency. The $TE_{0\,1}$ mode is the dominant mode in rectangular wave guides. Terman states (*Radio Engineer's Handbook,* 1st Ed., p. 259) that . . . "if the dimensions of a rectangular guide are suitably chosen in relation to wave length, only the $TE_{0\,1}$ mode of propagation is possible, and one is assured that the fields in the guide will correspond to those of a single pure mode."

The mode of operation of a wave guide depends upon the guide cross section and the manner in which excitation is achieved.

EXCITATION OF WAVE GUIDE

Microwave energy is introduced into a wave guide either by means of electrostatic or electromagnetic coupling or by radiation. Excitation is introduced at one end of the guide and usually is accomplished by means of a small antenna *probe*, or *dipole*, or a *loop*. The mode of operation depends upon the method of excitation of the guide. However, several modes, with the desired one dominant, may be set up with any excitation device unless the guide dimensions favor a single mode. The exciting device must be placed in such a way that it will initiate at a suitable position and in the proper direction a field component to insure the desired mode. For a given mode, for example, an antenna probe might be so placed as to produce an electric field component of appropriate direction, or a current loop likewise might be placed to produce a magnetic field component in the proper position.

Figure 4 shows two of the several methods of introducing an antenna probe into a rectangular wave guide. At A, is shown the insertion for the $TM_{1\,1}$ mode. At B, is the insertion of a similar probe for the $TE_{0\,1}$ mode.

The pickup device for coupling energy out of the wave guide is placed at the latter's far end, and duplicates the exciting device.

Q, CHARACTERISTIC IMPEDANCE, AND ATTENUATION

While the inner walls of the wave guide do not possess infinite conductivity, they usually are highly polished and the field does not penetrate deeply into the metal. There is, as a result, very little energy loss per cycle per unit area of conducting wall. This condition corresponds to high Q. The Q of an air-filled rectangular wave guide is directly proportional to the ratio of the volume of the guide to its inside area and, as in other cases, is a function of signal frequency. Actual Q values have been found to be in tens of thousands, a value of 25,000 being possible for a rectangular, air-filled guide.

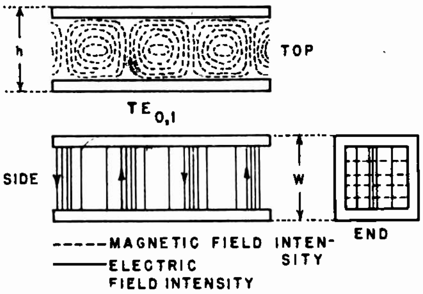


FIG. 1

The characteristic impedance of the rectangular guide is directly proportional to the *w* dimension (See Figure 1, Part 2) and varies with the mode of operation. When the *h* dimension and operating frequency are constant, the wave guide impedance will lie between 0 and 465 ohms. One of the accepted concepts of wave guide impedance, which is not identical with the meaning of characteristic impedance as associated with a device such as the coaxial cable, is the ratio of transverse electric field to transverse magnetic field.

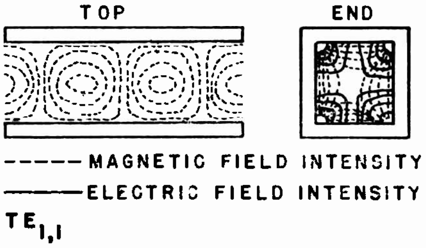


FIG. 2

Attenuation characteristics result from the finite conductivity of the inner walls of the practical air-filled guide. Each reflection is accomplished by a skin current component, however minute, at the wall. This component will be high for a large number of reflections, so that attenuation is expected to be higher at the longer wavelengths, for this reason. On the other hand, attenuation is high also at much shorter wavelengths because of the increased value of skin

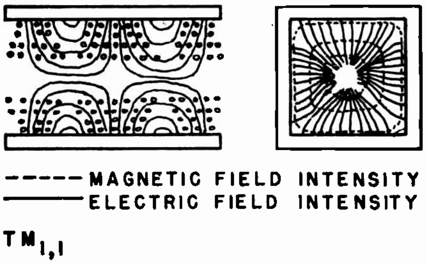


FIG. 3

losses at those wavelengths. Due to the high-pass filter action of the guide, attenuation is total below cutoff, it being impossible to maintain the wave within the guide below that point, as was shown in Part 2 of this series. Typical attenuation figures for a rectangular, air-filled, copper wave guide of 1″ x 2″ size do not exceed 0.1 db per foot for frequencies between 2000 and 50,000 Mc. Somewhat more severe attenuation is encountered in wave guides filled with solid dielectric material because of the increased losses in the dielectric.

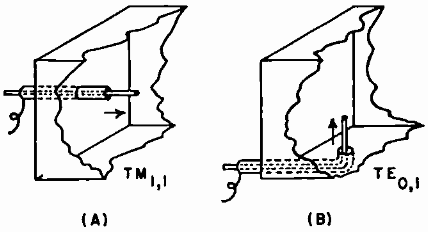


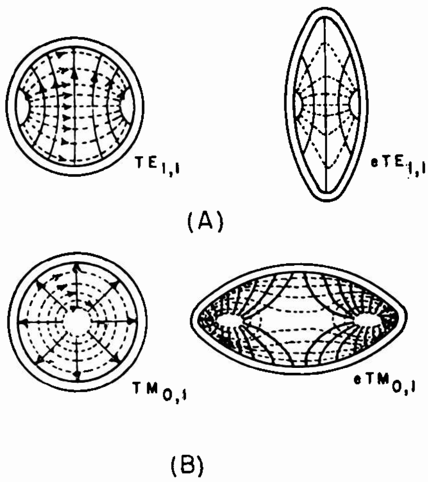
FIG. 4

CIRCULAR AND ELLIPTICAL WAVE GUIDES

Cylindrical wave guides include those types with circular and elliptical cross sections. These guides, like the rectangular types, may be completely hollow or dielectric-filled. The field equations for the cylindrical guide, which will not be enumerated in this paper, differ from those that apply to the rectangular guide.

Field distributions in circular and elliptical guides are depicted for two modes of operation, in Figure 5. 5-A shows the $TE_{1\,1}$ mode which is dominant in a circular wave guide. The

$TM_{0\,1}$ mode is shown at 5-B. Compare these field patterns with the distributions for the same modes in rectangular wave guides (Figures 1 and 3). The other fundamental modes, not shown, have the same notation as those given previously for rectangular guides. In practical use, circular wave guides occasionally become deformed mechanically and assume characteristics determined by the resulting ellipticity.



——— ELECTRIC FIELD INTENSITY

------- MAGNETIC FIELD INTENSITY

FIG. 5

In a circular wave guide, the ratio of diameter to wavelength determines the cutoff wavelength. This wavelength will vary with the eccentricity in the elliptical guide. Attenuation in the cylindrical types varies with frequency and conductor losses, as in the case of rectangular guides, and in addition it is affected (in some modes) positively or negatively by ellipticity. The attenuation figure will rise in the case of dielectric-filled guides because of losses in the filler material.

Excitation of the cylindrical wave guide is accomplished in a manner similar to the technique with rectangular guides. Energy also is coupled out of the circular or elliptical guide in a similar manner. The mode depicted by the circular pattern in Figure 5-B is the result of locating an antenna probe at one end of the guide, along the longitudinal axis and pointed in the direction of propagation, down the guide. We will not enter into a discussion of the specific application of probes and loops for input and output coupling, but will refer the reader instead to the reference list at the end of this article.

NOTES ON PRACTICAL APPLICATION

While we cannot hope to cover the many interesting aspects of practical wave guide operation in this limited space, we direct the reader's attention to the following notes which will stimulate closer investigation on the part of serious students and experimenters.

(1) Where microwave energy is to be transmitted between points, such as between a transmitter and antenna matching device, it may be propagated more efficiently through a wave guide than through other transmission line systems.

(2) Since the fields do not penetrate the wave guide walls, several guides may be run adjacent without interference.

(3) Several waves may be transmitted simultaneously through a wave guide, provided each has an appropriate mode and that separate, polarized excitation and pickup devices are provided for each desired mode.

(4) A wave guide may be made to discriminate between transmitted waves by (a) altering its cross section at a particular point or (b) inserting at the same point a circular metal disc with a central aperture.

(5) Quarter-wave lengths of wave guide may be employed as "impedance inverters" in the same manner as quarter-wave lines are employed for this purpose.

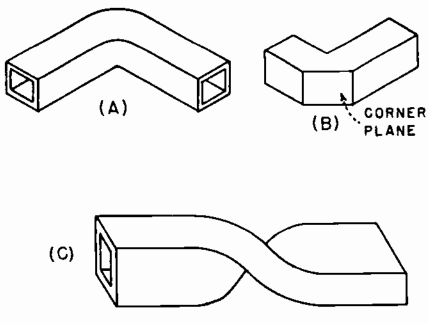


FIG. 6

(6) A wave guide may be flared out at its open end in order to obtain a horn for directional radiation.

(7) A ½-wavelength long wave guide, which is closed at each end by means of metal discs or plates, may be employed as a transformer or as a tuned circuit by introducing excitation ¼ wavelength from one end. Standing waves, resulting from reflections from the closed ends of the pipe, give rise to the effects of resonance and reinforcement.

(8) Both cylindrical and rectangular waves guides may be bent (See Figure 6-A), provided the bend is not sharp. They likewise may be turned sharply to form corners (See Figure 6-B), provided a suitably dimensioned metal plane is mounted angularly at the corner, or they may be twisted (See Figure 6-C).

(9) An opening is reflected from the junction of one wave guide with a second shorted wave guide that is ¼ wavelength long or is some multiple of a quarter wavelength in length.

(10) A shorted wave guide section which is ½ wavelength or some multiple of ½ wavelength long, reflects a solid barrier where it is joined to another wave guide.

(11) A movable metal partition inserted into a wave guide parallel to the direction of propagation produces an attenuator. Maximum attenuation occurs when the partition is all the way in.

(12) If the ends of a wave guide ½ wavelength long are closed and energy is injected at a point ¼ wavelength from either closed end, reflections between the various inner walls will be of the proper phase to produce a resonant reinforcement at the injection point. The wave guide thus may be made to function as a step-up transformer.

(13) A crystal diode probe may be inserted into a narrow slot cut parallel to the axis in a wave guide section and situated in an electric field maximum, and standing-wave ratios checked. In this application, the wave guide section is analogous to the familiar "slotted coaxial line" used for ultra-high-frequency measurements.

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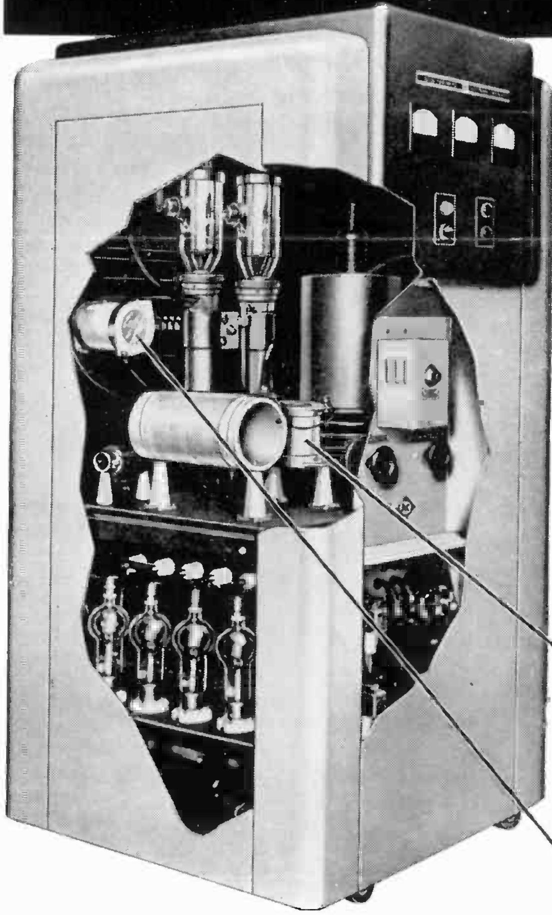

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.0001	35,000	1940-203	10.	6.	2.2	.8
.00015	35.000	1940-204	13.	8.	3.	1.2
.0002	35,000	1940-205	16.	12.	4.	1.5
.00025	35,000	1940-206	17.	13.	5.	2.0
.0003	35.000	[illegible]	[illegible]	15.	6.	2.4
.00035	35,000	[illegible]	[illegible]	15.	7.	2.5
[illegible]	35,000	[illegible]	[illegible]	16.	8.	3.3
.0005	[illegible]	[illegible]	[illegible]	20.	10.	4.
.0006	[illegible]	[illegible]	[illegible]	22	10.	4.5
.0007	[illegible]	[illegible]	[illegible]	22.	12.	5.
.0008	[illegible]	[illegible]	[illegible]	[illegible]	12.	6.
.001	[illegible]	[illegible]	[illegible]	[illegible]	14.	8.
.00125	[illegible]	[illegible]	[illegible]	[illegible]	15.	8.
.0015	35,000	[illegible]	[illegible]	[illegible]	18.	10.
.002	30,000	[illegible]	[illegible]	[illegible]	21.	11.5
.0025	25,000	[illegible]	[illegible]	[illegible]	22.	12.
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