The Lenkurt Demodulator

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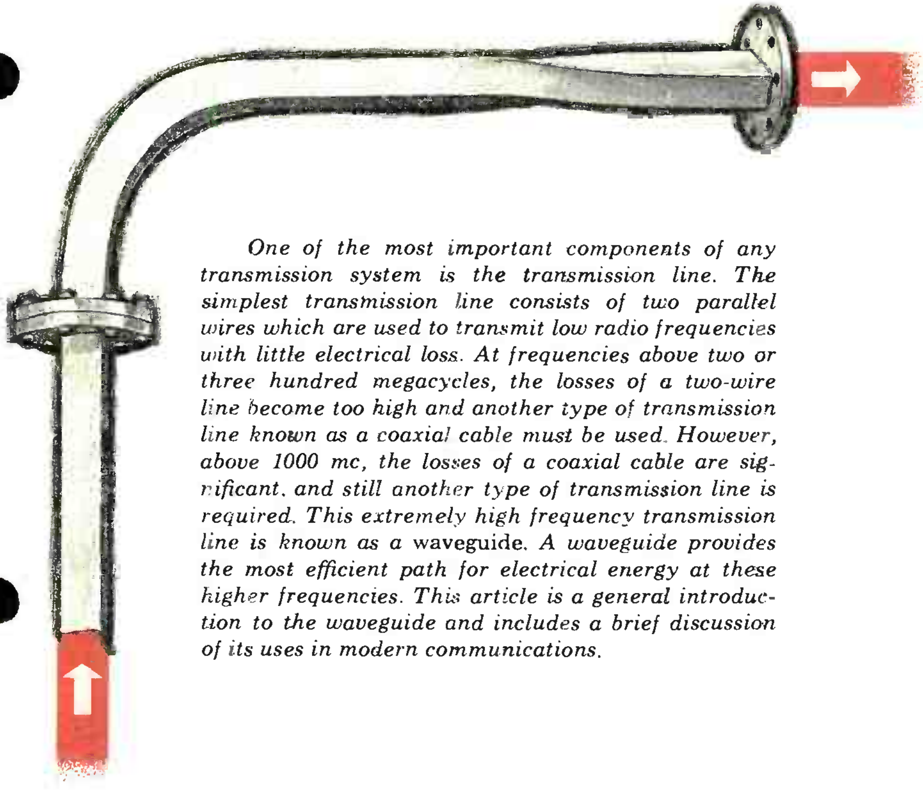
Characteristics of WAVEGUIDES



One of the most important components of any transmission system is the transmission line. The simplest transmission line consists of two parallel wires which are used to transmit low radio frequencies with little electrical loss. At frequencies above two or three hundred megacycles, the losses of a two-wire line become too high and another type of transmission line known as a coaxial cable must be used. However, above 1000 mc, the losses of a coaxial cable are significant, and still another type of transmission line is required. This extremely high frequency transmission line is known as a waveguide. *A waveguide provides the most efficient path for electrical energy at these higher frequencies. This article is a general introduction to the waveguide and includes a brief discussion of its uses in modern communications.*

The number of signals which may be transmitted over a given facility is directly proportional to the available frequency bandwidth. As is generally known, it is possible to group many independent message signals together and transmit them simultaneously over a single transmission facility. Broadband radio facilities occupying bandwidths of several megacycles are in common use today. The *waveguide* is a significant component of such systems.

The pioneer in the early experimental phase of the microwave field was Heinrich Hertz. Though his experiments were confined to relatively low microwave frequencies, his findings were outstanding accomplishments for the late 19th century. In the middle 1930's the practical applications of waveguides as transmission systems for microwaves were discovered. But it was not until the beginning of World War II that extensive exploitation of the microwave region was initiated. The benefits of microwave for high-frequency radar, such as improved directivity and resolution, brought forth the microwave spectrum as a very useful medium. After the war, microwave radio systems were developed that could transmit many hundreds of voice messages, and even television signals. Only because of the reach for higher and higher frequencies and the associated broad bandwidth capabilities did the waveguide find its ultimate and most efficient use as a low-loss transmission line.

Description

A waveguide is simply a single hollow metallic conductor, either rigid or flexible, which transfers electrical energy from one point to another. That it is possible to transmit electrical energy through a single conducting medium may seem strange to those accustomed to thinking in terms of currents and voltages along a two-wire transmission line. When considering energy transfer in a waveguide, it is easier to think of electromagnetic waves propagating through the waveguide in the same manner that radio waves propagate in space. A two-wire transmission line can, however, be analyzed using the electromagnetic field concepts, but it is more convenient to treat it in terms of voltages and currents. With a waveguide it is impossible to measure absolute values of voltage and current.

The shape of a waveguide may be rectangular, circular, or elliptical. By far the most common is the rectangular waveguide. It might be speculated that circular waveguides are preferable to rectangular waveguides, just as circular pipes find common application in carrying fluids. But the waves in a circular waveguide tend to *twist* as they travel through the structure. However, the circular type waveguide does find use with rotating antennas which require a rotating joint input. Elliptical waveguides are normally flexible, and are used for bends, and to reduce the close physical tolerances required of a rigid waveguide system. This article is concerned mainly with the characteristics of the more commonly used rectangular-shaped waveguide.

Modes

A waveguide is capable of transmitting microwave energy in a number of different electric and magnetic field configurations. The configuration in which energy propagates through a waveguide is referred to as the *mode*. A particular mode depends on the operating frequency and the physical dimensions of the waveguide.

Generally, there are two fundamental classes of modes that may appear in a waveguide. In one class the electric field is always perpendicular to the direction

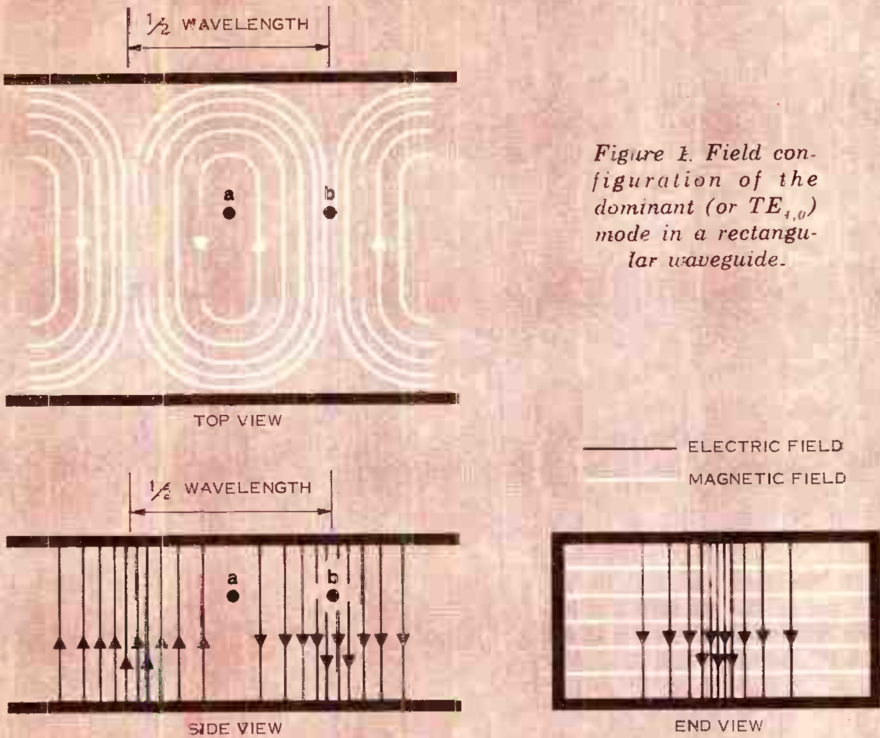


Figure 1. Field configuration of the dominant (or $TE_{1,0}$) mode in a rectangular waveguide.

of propagation. This class of modes is known as the TE or *transverse electric* class. In the second class of modes, the magnetic field is always perpendicular to the direction of propagation. This class is known as the TM or *transverse magnetic* class. The two fields are mutually perpendicular to each other and oriented at right angles to the direction of propagation.

The fields in the waveguide which make up these modes obey certain physical laws. Also, each mode has a *cutoff frequency*. This is the lowest frequency that will propagate through a waveguide while operating in a particular mode. Energy at frequencies below the cutoff frequency is greatly attenuated, while energy above the cutoff frequency is transmitted with very little attenuation.

The simplest or lowest order mode in a waveguide is called the *dominant mode*, and is the one most often used. Figure 1 shows the field pattern of the dominant mode in a rectangular waveguide. The black lines are voltage lines and indicate the direction of the electric field; the white lines indicate the magnetic field. In the end view, there is an electric field intensity between the narrow dimension sides of the waveguide which is maximum at the center. This is indicated by more voltage lines appearing in the center of the waveguide than toward its edges. The magnetic field, shown by the white lines, consists of closed loops of magnetic flux.

It should be noted that as the wave propagates along the waveguide, the electric and magnetic fields move together. Figure 1 represents the electromagnetic field as it exists at one instant of time. Although the amplitude at position *a* has zero intensity, a quarter cycle later the amplitude at position *a* will be the same as the present amplitude at position *b*.

The particular mode in each class is designated by two subscripts (for example, $TE_{1,0}$). The first subscript (1) indicates the number of half-wave variations of the electric field intensity across the wide dimension of the waveguide. The second subscript (0) denotes the number of half-wave variations across the narrow dimension. In Figure 1, the voltage intensity varies from zero to a maximum and back to zero across the wide dimension, which is one-half wavelength. Across the narrow dimension there is no variation in voltage intensity. Thus, in the transverse electric mode (TE) the subscripts 1 and 0 are added. The $TE_{1,0}$ mode is the dominant mode in a rectangular waveguide. Other subscripts designate higher order modes.

Many higher order modes other than the dominant mode can exist in a waveguide. But the common practice is to design the waveguide to propagate the dominant mode and suppress all others. The width of the usual rectangular waveguide is greater than one-half wavelength but less than one wavelength of the operating frequency. The height of the waveguide is then made about one-half the width. These dimensions are small enough to prevent higher order modes from forming, and give a cutoff frequency which is sufficiently below the operating frequency.

The dominant mode is more commonly used because it is an *exclusive* mode and, in its frequency range, prevents other higher order modes from forming, and because it gives the lowest cutoff frequency for a particular waveguide. Also, it provides low power dissipation, and requires smaller and less expensive waveguiding structures. Further, it gives the simplest field pattern, and is not as susceptible to impedance mismatches and reflections as the more complex higher order modes.

Characteristic Impedance

The waveguide has a characteristic impedance that is similar to the characteristic impedance of a two-wire transmission line. Therefore, the waveguide must be terminated by an impedance

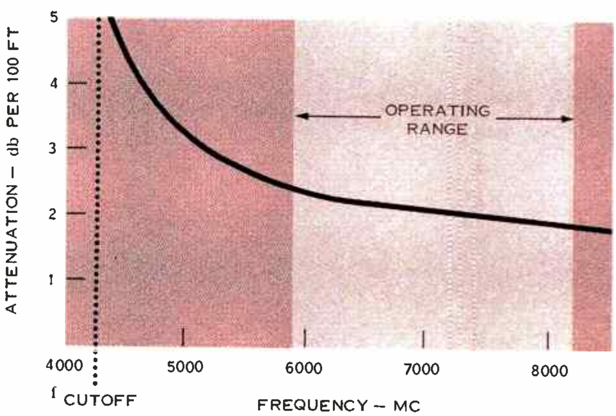


Figure 2. Attenuation versus frequency characteristics for a typical rectangular waveguide.

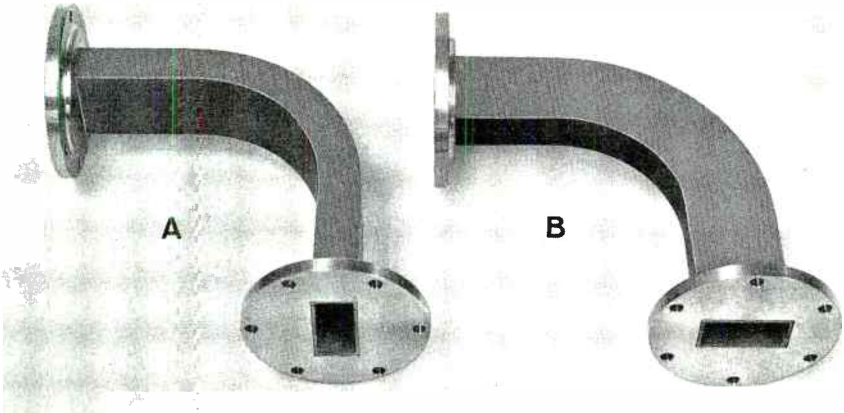


Figure 3. Two types of 90° bends for rectangular waveguide. Because the bend of waveguide A is in the plane of the electric field, it is referred to as an E bend. Waveguide B is referred to as an H bend because the bend is in the plane of the magnetic field.

equal to its characteristic impedance to prevent reflected waves. In a two-wire transmission line, the characteristic impedance is determined by the structure of the line and is relatively insensitive to frequency over a wide range. In contrast, the waveguide impedance is a direct function of frequency. The wave impedance of a rectangular waveguide in the dominant mode is given by the equation:

$$Z_0 = \frac{120\pi}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \text{ ohms}$$

where

f_c = *cutoff frequency, and*
f = *operating frequency.*

As can be seen from the equation, when the operating frequency is equal to the cutoff frequency, the waveguide impedance in infinite. Only by having the operating frequency greater than the cutoff frequency does the waveguide impedance achieve a finite value.

One method of achieving a good match between the waveguide and the load is, of course, to design the waveguide so that the load impedance completely absorbs all of the energy in the forward or *incident* wave. Another approach, however, is to set up a wave near the load that is equal in magnitude but opposite in phase from the wave reflected by the load. In this way, the injected wave and the wave reflected from the load cancel each other. This can be done only over a relatively narrow band of frequencies.

The voltage standing wave ratio (vswr) is an important parameter to consider when dealing with waveguides. The value of vswr determines whether or not the waveguide is correctly terminated in its characteristic impedance. As with a two-wire transmission line, the optimum vswr is 1:1 and this occurs when the load completely absorbs all the energy in the incident wave.

Losses

The propagation of energy through a waveguide is accompanied by a certain amount of attenuation as a result of the current induced in the walls of the waveguide. The resistivity that the induced current encounters is the result of the skin effect losses in the waveguide, and is proportional to frequency and the resistance of the waveguide material.

The energy loss is conveniently expressed in decibels of attenuation per unit length. Figure 2 shows the attenuation versus frequency characteristics of a typical waveguide. A standard size waveguide for 6000 to 8000 mc microwave systems has a loss of approximately 2½ db per hundred feet.

To minimize resistivity, the inner walls of the waveguide can be plated with a layer of silver. Because of skin effect, most of the energy flows near the surface of the waveguide walls, and only a very thin plating is needed to reduce the resistance of the waveguide walls.

Physical Characteristics

The dimensions of a waveguide are inversely proportional to the lowest frequency which it can propagate. The larger the waveguide, the lower the cutoff frequency and, conversely, the higher the frequency, the smaller the waveguide.

For a rectangular waveguide, the maximum wavelength of a transmitted wave is equal to twice the width of the waveguide. To transmit energy through a waveguide at 1000 mc, the width must be about 6 inches. It is only at frequencies higher than this that the required dimensions become small enough to make the use of waveguides practicable.

Because of the possibility of unwanted higher order modes appearing, it is common practice to operate waveguides over a relatively narrow frequency range. By properly selecting the frequency range, it is possible to operate far enough from the cutoff frequency, but within the frequency region where modes other than the dominant mode can be prevented.

In rectangular waveguides, higher order mode suppression is most effective when the ratio of width to height is 2 to 1. In contrast, if the waveguide were square there would be no frequency range over which only a single mode could propagate. The 2 to 1 ratio gives the best mode separation of all possible physical proportions.

The table on page 7 lists the characteristics of standard rectangular waveguide types used between 1700 and 15000 megacycles. The values given are for the dominant (or $TE_{1,0}$) mode. The Radio-Electronics Television Manufacturers Association (RETMA) and Army-Navy designations are also given, since they are the common means used to identify particular rectangular waveguides which have become standard.

At frequencies below about 3000 mc, the size of the waveguide has to be so large to propagate the dominant mode that weight and costs become excessive. Consequently, coaxial transmission lines are more often used in the microwave region below 3000 mc. Above 3000 mc the desirable dimensions of the waveguide become sufficiently small—and the losses of a coaxial line become extremely high—so that the waveguide is more practical and economical to use.

Most waveguides are constructed from oxygen-free high-conductivity copper, because this material has excellent inherent electrical characteristics. In some cases, brass is used for unusual waveguide shapes, because machining

TABLE OF STANDARD RECTANGULAR WAVEGUIDES (1700 TO 15000 MC)

Frequency Range (megacycles)	Cutoff Frequency (megacycles)	Outside Dimensions (inches)	Wall Thickness (inches)	RETMA Designation	Army-Navy Type No.
1700-2600	1375	4.460×2.310	0.080	WR430	RG-104/U
2200-3300	1735	3.560×1.860	0.080	WR340	- - -
2600-3950	2080	3.000×1.500	0.080	WR284	RG-48/U
3300-4900	2590	2.418×1.273	0.064	WR229	- - -
3950-5850	3160	2.000×1.000	0.064	WR187	RG-49/U
4900-7050	3710	1.718×0.923	0.064	WR159	- - -
5850-8200	4290	1.500×0.750	0.064	WR137	RG-50/U
7050-10000	5260	1.250×0.625	0.064	WR112	RG-51/U
8200-12400	6560	1.000×0.500	0.050	WR90	RG-52/U
10000-15000	7880	0.850×0.475	0.050	WR75	- - -

and fabrication are much easier to accomplish with this material.

The Waveguide Run

The physical path of the *waveguide run* between the radio equipment and the microwave antenna cannot always be a straight line, but is usually made up of a combination of straight, curved, and flexible sections of waveguide. Two typical 90° curved sections of waveguide are shown in Figure 3. Curved sections tend to introduce reflections and contribute power loss, but these can be kept to a minimum if the radius of the curved section is never less than two wavelengths of the transmitted signal.

Other losses can be attributed to a number of factors. Size differences, misalignment, twists or bows, dents, and scratches all contribute losses and reflections. Since the flanges of adjoining waveguide sections are difficult to keep smooth and square with the waveguide axis, extreme judgment and care must be exercised in establishing a waveguide system so that a minimum number of sections are used.

Residual moisture appearing on the inside walls of a waveguide causes corrosion and increases attenuation. Therefore, an outdoor waveguide run is normally pressurized with dry air or nitrogen to eliminate this problem.

Conclusion

This article has covered some of the advantages of waveguides over other types of transmission lines. To sum up, the waveguide is capable of transmitting much higher powers than other types of transmission lines and at higher frequencies.

In waveguides of the types commonly employed, and for ordinary runs, attenuation is negligible. Waveguides with extremely low losses and reflections are produced by modern manufacturing processes, and with careful installation excellent performance can be achieved.

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