10

Waveguides, Resonators and Components

It was seen in Chapter 8 that electromagnetic waves will travel from one point to another, if suitably radiated. Chapter 7 showed how it is possible to guide radio waves from one point to another in an enclosed system by the use of transmission lines. This chapter will deal with *waveguides*. Any system of conductors and insulators for carrying electromagnetic waves could be called a *waveguide*, but it is customary to reserve this name for specially constructed hollow metallic pipes. They are used at microwave frequencies, for the same purposes as transmission lines were used at lower frequencies. Waveguides are preferred to transmission lines because they are much less lossy at the highest frequencies and for other reasons that will become apparent through this chapter.

The objective of this chapter is to acquaint the student with the general principles of waveguide propagation and rectangular, circular and odd-shaped waveguides. Methods of exciting waveguides as well as basic waveguide components are then described, as are impedance matching and attenuation. *Cavity resonators* are the waveguide equivalents of tuned transmission lines but are somewhat more complex because of their three-dimensional shapes. The final major section of the chapter deals with additional waveguide components, such as *directional couplers*, *isolators*, *circulators*, *diodes*, *diode mounts* and *switches*.

Having studied this chapter, students should have a very good understanding of waveguides and associated components, their physical appearance, behavior and properties. They should also have a clear understanding of how microwaves are guided over long distances.

OBJECTIVES

Upon completing the material in Chapter 10, the student will be able to:

Explain the basic theory of operation and construction of a waveguide.

Define the term *skin effect*.

Calculate the (λ_0), the cutoff wavelength.

Name the various energy modes and understand their meanings.

Discuss the advantages of the numerous waveguide shapes.

Understand coupling techniques and where they are used.

Calculate waveguide attenuation.

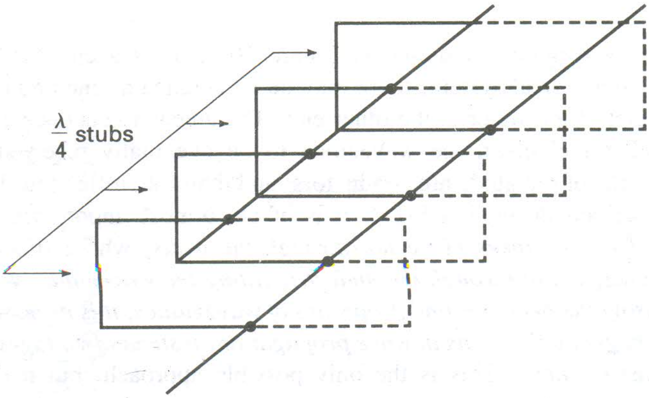

FIGURE 10-1 Creating a waveguide.

10-1 RECTANGULAR WAVEGUIDES

The student may recall from Chapter 7 that the term *skin effect* (see Section 7-1.2) indicated that the majority of the current flow (at very high frequencies) will occur mostly along the surface of the conductor and very little at the center. This phenomenon has led to the development of hollow conductors known as *waveguides*.

To simplify the understanding of the waveguide action, we refer to Section 7-1.5, which explained how the quarter-wave shorted stub appeared as a parallel resonant circuit (Hi Z) to the source. This fact can be used in the analysis of a waveguide; i.e., a transmission line can be transformed into a waveguide by connecting multiple quarter-wave shorted stubs (see Figure 10-1). These multiple connections represent a Hi Z to the source and offer minimum attenuation of a signal.

In a similar way, a pipe with *any* sort of cross section could be used as a waveguide (see Figure 10-2), but the simplest cross sections are preferred. Waveguides with constant rectangular or circular cross sections are normally employed, although other shapes may be used from time to time for special purposes. With regular transmission lines and waveguides, the simplest shapes are the ones easiest to manufacture, and the ones whose properties are simplest to evaluate.

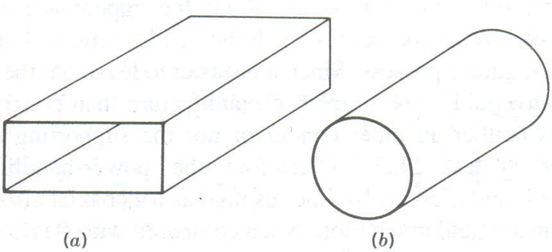

FIGURE 10-2 Waveguides. (*a*) Rectangular; (*b*) circular.

10-1.1 Introduction

A rectangular waveguide is shown in Figure 10-2, as is a circular waveguide for comparison. In a typical system, there may be an antenna at one end of a waveguide and a receiver or transmitter at the other end. The antenna generates electromagnetic waves, which travel down the waveguide to be eventually received by the load.

The walls of the guide are conductors, and therefore reflections from them take place, as described in Section 8-1.2. It is of the utmost importance to realize that *conduction of energy takes place not through the walls,* whose function is only to confine this energy, *but through the dielectric filling the waveguide,* which is usually air. *In discussing the behavior and properties of waveguides, it is necessary to speak of electric and magnetic fields, as in wave propagation, instead of voltages and currents,* as in transmission lines. This is the only possible approach, but it does make the behavior of waveguides more complex to grasp.

Applications Because the cross-sectional dimensions of a waveguide must be of the same order as those of a wavelength, use at frequencies below about 1 GHz is not normally practical, unless special circumstances warrant it. Some selected waveguide sizes, together with their frequencies of operation, are presented in Table 10-1.

The table shows how waveguide dimensions decrease as the frequency is increased (and therefore wavelength is shortened). It does not show the several waveguides larger than the WR650, nor does it show many of the overlapping sizes that are also made. Note that the reason for the rather odd dimensions is that waveguides originally were made to imperial measurements (e.g., 3.00 × 1.50 in) and have subsequently been relabeled in millimeters, not remade in round millimeter sizes. It is seen that waveguides have dimensions that are convenient in the 3- to 100-GHz range, and somewhat inconvenient much outside this range. Within the range, waveguides are generally superior to coaxial transmission lines for a whole spectrum of microwave applications, for either power or low-level signals.

Both waveguides and transmission lines can pass several signals simultaneously, but in waveguides it is sufficient for them to be propagated in different *modes* to be separated. They do not have to be of different frequencies. A number of waveguide components are similar if not identical to their coaxial counterparts. These components include *stubs, quarter-wave transformers, directional couplers,* and *taper sections.* Finally, the Smith chart may be used for waveguide calculations also. The operation of a very large number of waveguide components may best be understood by first looking at their transmission-line equivalents.

Advantages The first thing that strikes us about the appearance of a (circular) waveguide is that it looks like a coaxial line with the insides removed. This illustrates the advantages that waveguides possess. Since it is easier to leave out the inner conductor than to put it in, waveguides are simpler to manufacture than coaxial lines. Similarly, because there is neither an inner conductor nor the supporting dielectric in a waveguide, flashover is less likely. Therefore the power-handling ability of waveguides is improved, and is about 10 times as high as for coaxial air-dielectric rigid cables of similar dimension (and much more when compared with flexible solid-dielectric cable).

TABLE 10-1 Selected Rectangular Waveguides

USEFUL FREQUENCY RANGE GHz	OUTSIDE DIMENSIONS, mm	WALL THICKNESS, mm	RETMA* DESIGNATION	JAN† TYPE NO.	THEORETICAL AVERAGE ATTENUATION, dB/m	THEORETICAL AVERAGE (CW) POWER RATING, kW
1.12–1.70	169 × 86.6	2.0	WR650	RG-69/U	0.0052	14,600
1.70–2.60	113 × 58.7	2.0	WR430	RG-104/U	0.0097	6400
2.60–3.95	76.2 × 38.1	2.0	WR284	RG-48/U	0.019	2700
3.95–5.85	50.8 × 25.4	1.6	WR187	RG-49/U	0.036	1700
5.85–8.20	38.1 × 19.1	1.6	WR137	RG-50/U	0.058	635
8.20–12.40	25.4 × 12.7	1.3	WR90	RG-52/U	0.110	245
12.40–18.00	17.8 × 9.9	1.0	WR62	RG-91/U	0.176	140
18.0–26.5	12.7 × 6.4	1.0	WR42	RG-53/U	0.37	51
26.5–40.0	9.1 × 5.6	1.0	WR28	RG-96/U	0.58	27
40.0–60.0	6.8 × 4.4	1.0	WR19	—	0.95¶	13
60.0–90.0	5.1 × 3.6	1.0	WR12	RG-99/U	1.50¶	5.1
90.0–140	4.0 (diam.)‡	2.0 × 1.0§	WR8	RG-138/U	2.60¶	2.2
140–220	4.0 (diam.)	1.3 × 0.64	WR5	RG-135/U	5.20¶	0.9
220–325	4.0 (diam.)	0.86 × 0.43	WR3	RG-139/U	8.80¶	0.4

*Radio-Electronic-Television Manufacturers' Association.

†Joint Army-Navy (JAN) numbers are shown for copper waveguides (there are also aluminum waveguides with identical dimensions but different US military numbers and somewhat iower attenuations), except for the last five numbers, which are for silver waveguides. Where no number is given, none exists.

‡Waveguides of this size or smaller are circular on the outside.

§Internal dimensions given instead of wall thickness for this waveguide and the smaller ones.

¶Approximate measurements.

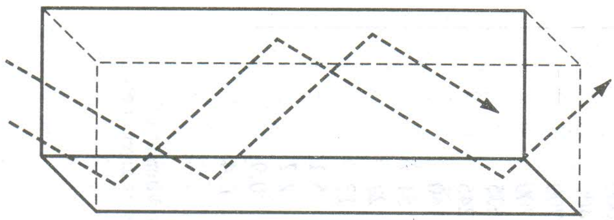

FIGURE 10-3 Method of wave propagation in a waveguide.

There is nothing but air in a waveguide, and since propagation is by reflection from the walls instead of conduction along them, power losses in waveguides are lower than in comparable transmission lines (see Figure 10-3). A 41-mm air-dielectric cable has an attenuation of 4.0 dB/100 m at 3 GHz (which is very good for a coaxial line). This rises to 10.8 dB/100 m for a similar foam-dielectric flexible cable, whereas the figure for the copper WR284 waveguide is only 1.9 dB/100 m.

Everything else being equal, waveguides have advantages over coaxial lines in mechanical simplicity and a much higher maximum operating frequency (325 GHz as compared with 18 GHz) because of the different method of propagation.

10-1.2 Reflection of Waves from a Conducting Plane

In view of the way in which signals propagate in waveguides, it is now necessary to consider what happens to electromagnetic waves when they encounter a conducting surface. This is an extension of the work in Section 8-1.

Basic behavior An electromagnetic plane wave in space is transverse-electromagnetic, or TEM. The electric field, the magnetic field and the direction of propagation are mutually perpendicular. If such a wave were sent straight down a waveguide, it would not propagate in it. This is because the electric field (no matter what its direction) would be short-circuited by the walls, since the walls are assumed to be perfect conductors, and a potential cannot exist across them. What must be found is some method of propagation which does not require an electric field to exist near a wall and simultaneously be parallel to it. This is achieved by sending the wave down the waveguide in a zigzag fashion (see Figure 10-3), bouncing it off the walls and setting up a field that is maximum at or near the center of the guide, and zero at the walls. In this case the walls have nothing to short-circuit, and they do not interfere with the wave pattern set up between them. Thus propagation is not hindered.

Two major consequences of the zigzag propagation are apparent. The first is that the velocity of propagation in a waveguide must be less than in free space, and the second is that waves can no longer be TEM. The second situation arises because propagation by reflection requires not only a normal component but also a component in the direction of propagation (as shown in Figure 10-4) for either the electric or the magnetic field, depending on the way in which waves are set up in the waveguide. This extra component in the direction of propagation means that waves are no longer trans-

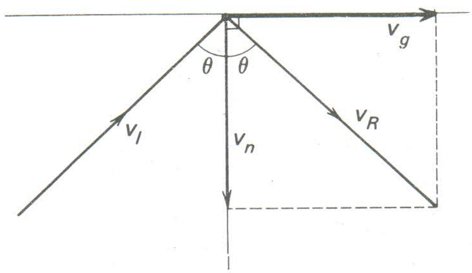

FIGURE 10-4 Reflection from a conducting surface.

verse-electromagnetic, because there is now either an electric or a magnetic additional component in the direction of propagation.

Since there are two different basic methods of propagation, names must be given to the resulting waves to distinguish them from each other. Nomenclature of these *modes* has always been a perplexing question. The American system labels modes according to the field component that behaves as it did in free space. Modes in which there is no component of electric field in the direction of propagation are called *transverse-electric* (*TE,* see Figure 10-5*b*) modes, and modes with no such component of magnetic field are called *transverse-magnetic* (*TM,* see Figure 10-5*a*). The British and European systems label the modes according to the component that has behavior different from that in free space, thus modes are called H instead of TE and E instead of TM. The American system will be used here exclusively.

Dominant mode of operation The natural mode of operation for a waveguide is called the *dominant mode*. This mode is the lowest possible frequency that can be propagated in a given waveguide. In Figure 10-6, half-wavelength is the lowest frequency where the waveguide will still present the properties discussed below. The mode of operation of a waveguide is further divided into two submodes. They are as follows:

1. $TE_{m,n}$ for the transverse electric mode (electric field is perpendicular to the direction of wave propagation)
2. $TM_{m,n}$ for the transverse magnetic mode (magnetic field is perpendicular to the direction of wave propagation)

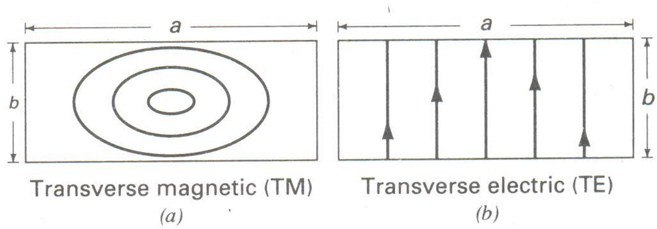

FIGURE 10-5 TM and TE propagation.

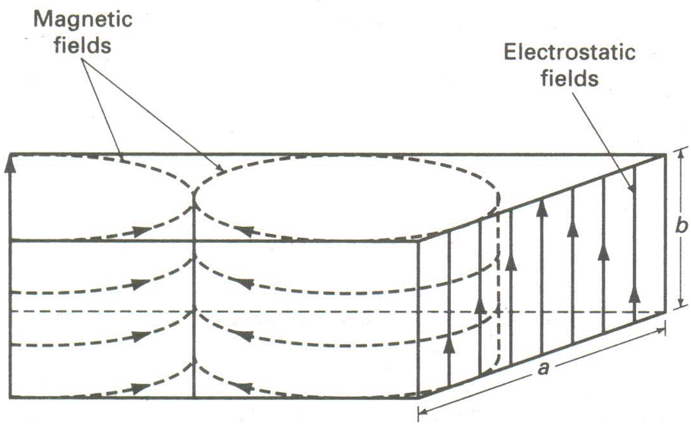

FIGURE 10-6 Dominant mode of waveguide operation.

m = number of half-wavelengths across waveguide width (a on Figure 10-6)
n = number of half-wavelengths along the waveguide height (b on Figure 10-6)

Plane waves at a conducting surface Consider Figure 10-7, which shows wavefronts incident on a perfectly conducting plane (for simplicity, reflection is not shown). The waves travel diagonally from left to right, as indicated, and have an angle of incidence θ.

If the actual velocity of the waves is v_c, then simple trigonometry shows that the velocity of the wave in a direction parallel to the conducting surface, v_g, and the velocity normal to the wall, v_n, respectively, are given by

$$v_g = v_c \sin \theta \tag{10-1}$$

$$v_n = v_c \cos \theta \tag{10-2}$$

As should have been expected, Equations (10-1) and (10-2) show that waves travel forward more slowly in a waveguide than in free space.

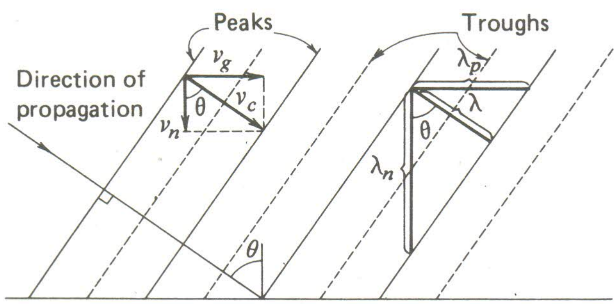

FIGURE 10-7 Plane waves at a conducting surface.

Parallel and normal wavelength The concept of *wavelength* has several descriptions or definitions, all of which mean the distance between two successive identical points of the wave, such as two successive crests. It is now necessary to add the phrase *in the direction of measurement,* because we have so far always considered measurement in the direction of propagation (and this has been left unsaid). There is nothing to stop us from measuring wavelength in any other direction, but there has been no application for this so far. Other practical applications do exist, as in the cutting of corrugated roofing materials at an angle to meet other pieces of corrugated material.

In Figure 10-7, it is seen that the wavelength in the direction of propagation of the wave is shown as λ, being the distance between two consecutive wave crests in this direction. The distance between two consecutive crests in the direction parallel to the conducting plane, or the wavelength in that direction, is λ_p, and the wavelength at right angles to the surface is λ_n. Simple calculation again yields

$$\lambda_p = \frac{\lambda}{\sin \theta} \tag{10-3}$$

$$\lambda_n = \frac{\lambda}{\cos \theta} \tag{10-4}$$

This shows not only that wavelength depends on the direction in which it is measured, but also that it is greater when measured in some direction other than the direction of propagation.

Phase velocity Any electromagnetic wave has two velocities, the one with which it propagates and the one with which it changes phase. In free space, these are "naturally" the same and are called the *velocity of light*, v_c, where v_c is the product of the distance of two successive crests and the number of such crests per second. It is said that the product of the wavelength and frequency of a wave gives its velocity, and

$$\begin{aligned} v_c &= f\lambda \\ &= 3 \times 10^8 \text{ m/s} \quad \text{in free space} \end{aligned} \tag{10-5}$$

For Figure 10-7 it was indicated that the velocity of propagation in a direction parallel to the conducting surface is $v_g = v_c \sin \theta$, as given by Equation (10-1). It was also shown that the wavelength in this direction is $\lambda_p = \lambda/\sin \theta$, given by Equation (10-3). If the frequency is f, it follows that the velocity (called the *phase velocity*) with which the wave changes phase in a direction parallel to the conducting surface is given by the product of the two. Thus

$$\begin{aligned} v_p &= f\lambda p \\ &= \frac{f\lambda}{\sin \theta} \qquad (10\text{-}6) \\ &= \frac{v_c}{\sin \theta} \qquad (10.7) \end{aligned}$$

where v_p = phase velocity.

A most surprising result is that there is an *apparent velocity,* associated with an electromagnetic wave at a boundary, which is greater than either its velocity of propagation in that direction, v_g, or its velocity in space, v_c. It should be mentioned that the theory of relativity has not been contradicted here, since neither mass, nor energy, nor signals can be sent with this velocity. It is merely the velocity with which the wave changes phase at a plane boundary, not the velocity with which it travels along the boundary. A number of other apparent velocities greater than the velocity of light can be shown to exist. For instance, consider sea waves approaching a beach at an angle, rather than straight in. The interesting phenomenon which accompanies this (it must have been noticed by most people) is that the edge of the wave appears to sweep along the beach must faster than the wave is really traveling, it is the *phase velocity* that provides this effect. The two velocities will be discussed again, in the next section.

10-1.3 The Parallel-Plane Waveguide

It was shown in Section 7-1.4, in connection with transmission lines, that reflections and standing waves are produced if a line is terminated in a short circuit, and that there is a voltage zero and a current maximum at this termination. This is illustrated again in Figure 10-8, because it applies directly to the situation described in the previous section, involving electromagnetic waves at a conducting boundary.

A rectangular waveguide has two pairs of walls, and we shall be considering their addition one pair at a time. It is now necessary to investigate whether the second wall in a pair may be added at any distance from the first, or whether there are any preferred positions and, if so, how to determine them. Transmission-line equivalents will continue to be used, because they definitely help to explain the situation.

Addition of a second wall If a second short circuit is added to Figure 10-8, care must be taken to ensure that it does not disturb the existing wave pattern (the feeding source must somehow be located between the two short-circuited ends). Three suitable positions for the second short circuit are indicated in Figure 10-9. It is seen that each of them is at a point of zero voltage on the line, and each is located at a distance from the first short circuit that is a multiple of half-wavelengths.

The presence of a reflecting wall does to electromagnetic waves what a short circuit did to waves on a transmission line. A pattern is set up and will be destroyed

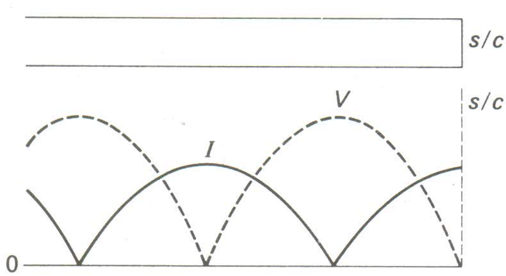

FIGURE 10-8 Short-circuited transmission line with standing waves.