CHAPTER 1

WAVEGUIDE THEORY AND APPLICATION

LEARNING OBJECTIVES

Upon completion of this chapter the student will be able to:

1. Describe the development of the various types of waveguides in terms of their advantages and disadvantages.
2. Describe the physical dimensions of the various types of waveguides and explain the effects of those dimensions on power and frequency.
3. Explain the propagation of energy in waveguides in terms of electromagnetic field theory.
4. Identify the modes of operation in waveguides.
5. Explain the basic input/output methods used in waveguides.
6. Describe the basic principles of waveguide plumbing.
7. Explain the reasons for and the methods of terminating waveguides.
8. Explain the basic theory of operation and applications of directional couplers.
9. Describe the basic theory of operation, construction, and applications of cavity resonators.
10. Describe the basic theory of operation of waveguide junctions.
11. Explain the operation of ferrite devices in terms of their applications.

INTRODUCTION TO WAVEGUIDE THEORY AND APPLICATION

That portion of the electromagnetic spectrum which falls between 1000 megahertz and 100,000 megahertz is referred to as the MICROWAVE region. Before discussing the principles and applications of microwave frequencies, the meaning of the term microwave as it is used in this module must be established. On the surface, the definition of a microwave would appear to be simple because, in electronics, the prefix "micro" normally means a millionth part of a unit. Micro also means small, which is a relative term, and it is used in that sense in this module. Microwave is a term loosely applied to identify electromagnetic waves above 1000 megahertz in frequency because of the short physical wavelengths of these frequencies. Short wavelength energy offers distinct advantages in many applications. For instance, excellent directivity can be obtained using relatively small antennas and low-power transmitters. These features are ideal for use in both military and civilian radar and communication applications. Small antennas and other small components are made possible by microwave frequency applications. This is an important consideration in shipboard equipment planning where space and weight are major problems. Microwave frequency usage is especially important in the design of shipboard radar because it makes possible the detection of smaller targets.

Microwave frequencies present special problems in transmission, generation, and circuit design that are not encountered at lower frequencies. Conventional circuit theory is based on voltages and currents while microwave theory is based on electromagnetic fields. The concept of electromagnetic field interaction is not entirely new, since electromagnetic fields form the basis of all antenna theory. However, many students of electronics find electromagnetic field theory very difficult to visualize and understand. This module will present the principles of microwave theory in the simplest terms possible but many of the concepts are still somewhat difficult to thoroughly understand. Therefore, you must realize that this module will require very careful study for you to properly understand microwave theory. Antenna fundamentals were covered in *NEETS*, Module 10, *Introduction to Wave Propagation, Transmission Lines, and Antennas*.

This module will show you the solutions to problems encountered at microwave frequencies, beginning with the transmission of microwave energy and continuing through to waveguides in chapter 1. Later chapters will cover the theory of operation of microwave components, circuits, and antennas. The application of these concepts will be discussed more thoroughly in later *NEETS* modules on radar and communications.

Q-1. What is the region of the frequency spectrum from 1000 MHz to 100,000 MHz called?

Q-2. Microwave theory is based upon what concept

WAVEGUIDE THEORY

The two-wire transmission line used in conventional circuits is inefficient for transferring electromagnetic energy at microwave frequencies. At these frequencies, energy escapes by radiation because the fields are not confined in all directions, as illustrated in figure 1-1. Coaxial lines are more efficient than two-wire lines for transferring electromagnetic energy because the fields are completely confined by the conductors, as illustrated in figure 1-2.

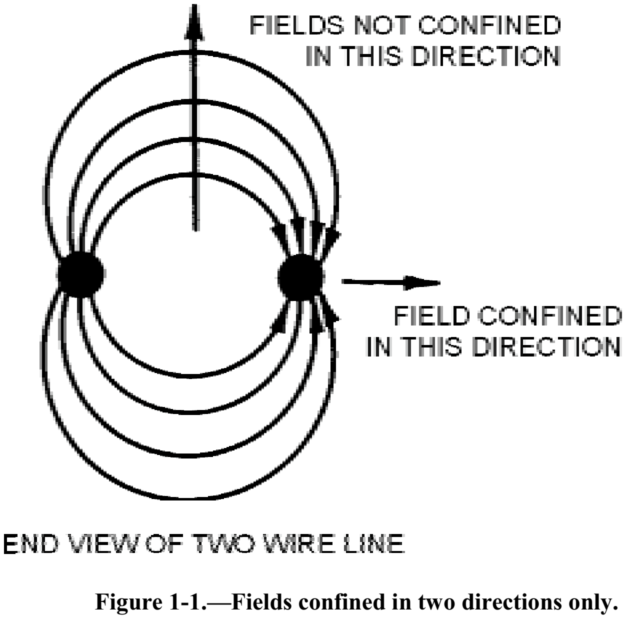


Figure 1-1.—Fields confined in two directions only.

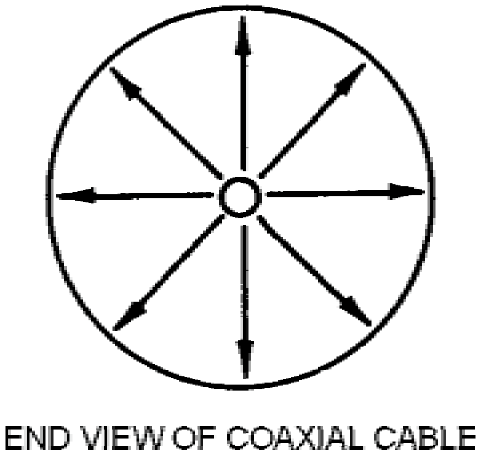


Figure 1-2.—Fields confined in all directions.

Waveguides are the most efficient way to transfer electromagnetic energy. WAVEGUIDES are essentially coaxial lines without center conductors. They are constructed from conductive material and may be rectangular, circular, or elliptical in shape, as shown in figure 1-3.

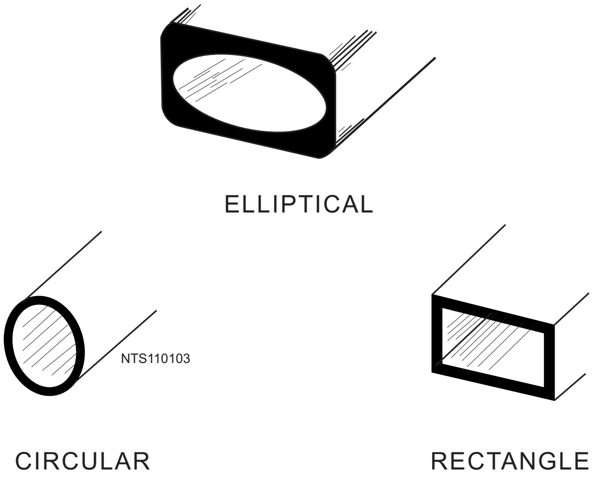


Figure 1-3.—Waveguide shapes.

Waveguide Advantages

Waveguides have several advantages over two-wire and coaxial transmission lines. For example, the large surface area of waveguides greatly reduces COPPER (I^2R) LOSSES. Two-wire transmission lines have large copper losses because they have a relatively small surface area. The surface area of the outer conductor of a coaxial cable is large, but the surface area of the inner conductor is relatively small. At microwave frequencies, the current-carrying area of the inner conductor is restricted to a very small layer at the surface of the conductor by an action called SKIN EFFECT.

Skin effect was discussed in *NEETS*, Module 10, *Introduction to Wave Propagation, Transmission Lines, and Antennas*, Chapter 3. Skin effect tends to increase the effective resistance of the conductor. Although energy transfer in coaxial cable is caused by electromagnetic field motion, the magnitude of the field is limited by the size of the current-carrying area of the inner conductor. The small size of the center conductor is even further reduced by skin effect and energy transmission by coaxial cable becomes less efficient than by waveguides. DIELECTRIC LOSSES are also lower in waveguides than in two-wire and coaxial transmission lines. Dielectric losses in two-wire and coaxial lines are caused by the heating of the insulation between the conductors. The insulation behaves as the dielectric of a capacitor formed by the two wires of the transmission line. A voltage potential across the two wires causes heating of the dielectric and results in a power loss. In practical applications, the actual breakdown of the insulation between the conductors of a transmission line is more frequently a problem than is the dielectric loss.

This breakdown is usually caused by stationary voltage spikes or "nodes" which are caused by standing waves. Standing waves are stationary and occur when part of the energy traveling down the line is reflected by an impedance mismatch with the load. The voltage potential of the standing waves at the points of greatest magnitude can become large enough to break down the insulation between transmission line conductors.

The dielectric in waveguides is air, which has a much lower dielectric loss than conventional insulating materials. However, waveguides are also subject to dielectric breakdown caused by standing waves. Standing waves in waveguides cause arcing which decreases the efficiency of energy transfer and can severely damage the waveguide. Also since the electromagnetic fields are completely contained within the waveguide, radiation losses are kept very low.

Power-handling capability is another advantage of waveguides. Waveguides can handle more power than coaxial lines of the same size because power-handling capability is directly related to the distance between conductors. Figure 1-4 illustrates the greater distance between conductors in a waveguide.

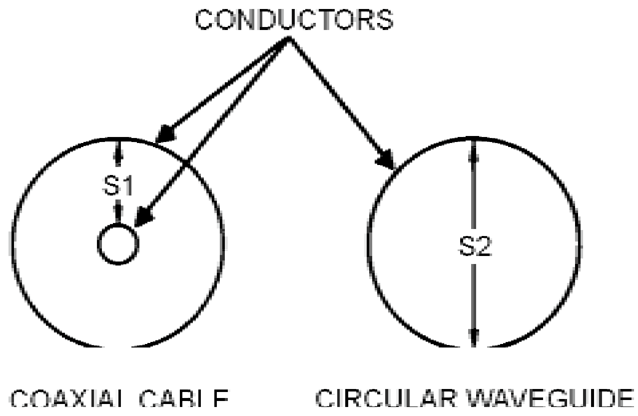


Figure 1-4.—Comparison of spacing in coaxial cable and a circular waveguide.

In view of the advantages of waveguides, you would think that waveguides should be the only type of transmission lines used. However, waveguides have certain disadvantages that make them practical for use only at microwave frequencies.

Waveguide Disadvantages

Physical size is the primary lower-frequency limitation of waveguides. The width of a waveguide must be approximately a half wavelength at the frequency of the wave to be transported. For example, a waveguide for use at 1 megahertz would be about 500 feet wide. This makes the use of waveguides at frequencies below 1000 megahertz increasingly impractical. The lower frequency range of any system using waveguides is limited by the physical dimensions of the waveguides.

Waveguides are difficult to install because of their rigid, hollow-pipe shape. Special couplings at the joints are required to assure proper operation. Also, the inside surfaces of waveguides are often plated with silver or gold to reduce skin effect losses. These requirements increase the costs and decrease the practicality of waveguide systems at any other than microwave frequencies.

Q-3. Why are coaxial lines more efficient at microwave frequencies than two-wire transmission lines?

Q-4. What kind of material must be used in the construction of waveguides?

Q-5. The large surface area of a waveguide greatly reduces what type of loss that is common in two-wire and coaxial lines?

Q-6. What causes the current-carrying area at the center conductor of a coaxial line to be restricted to a small layer at the surface?

Q-7. What is used as a dielectric in waveguides?

Q-8. What is the primary lower-frequency limitation of waveguides?

Developing the Waveguide from Parallel Lines

You may better understand the transition from ordinary transmission line concepts to waveguide theories by considering the development of a waveguide from a two-wire transmission line. Figure 1-5 shows a section of two-wire transmission line supported on two insulators. At the junction with the line, the insulators must present a very high impedance to ground for proper operation of the line. A low impedance insulator would obviously short-circuit the line to ground, and this is what happens at very high frequencies. Ordinary insulators display the characteristics of the dielectric of a capacitor formed by the wire and ground. As the frequency increases, the overall impedance decreases. A better high-frequency insulator is a quarter-wave section of transmission line shorted at one end. Such an insulator is shown in figure 1-6. The impedance of a shorted quarter-wave section is very high at the open-end junction with the two-wire transmission line. This type of insulator is known as a METALLIC INSULATOR and may be placed anywhere along a two-wire line. Note that quarter-wave sections are insulators at only one frequency. This severely limits the bandwidth, efficiency, and application of this type of two-wire line.

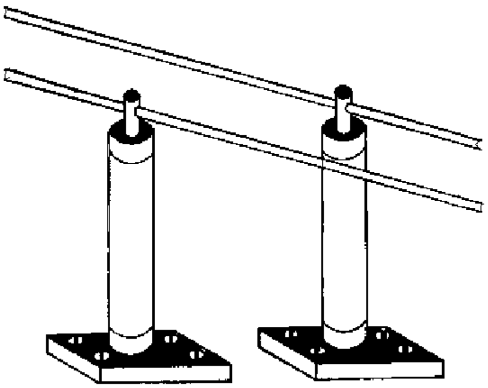


Figure 1-5.—Two-wire transmission line using ordinary insulators.

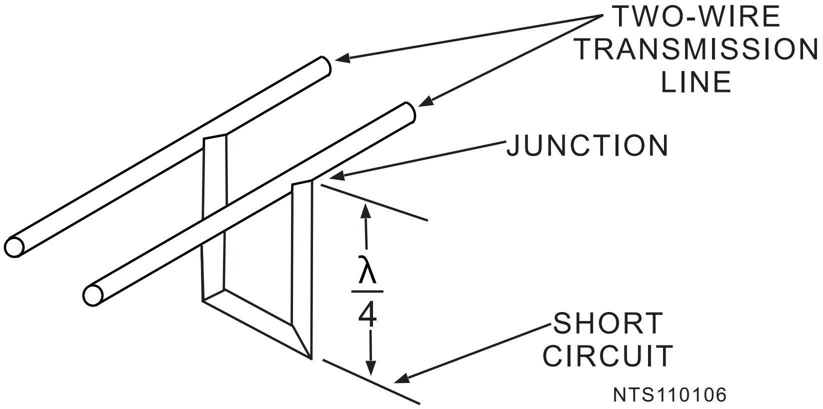


Figure 1-6.—Quarter-wave section of transmission line shorted at one end.

Figure 1-7 shows several metallic insulators on each side of a two-wire transmission line. As more insulators are added, each section makes contact with the next, and a rectangular waveguide is formed. The lines become part of the walls of the waveguide, as illustrated in figure 1-8. The energy is then conducted within the hollow waveguide instead of along the two-wire transmission line.

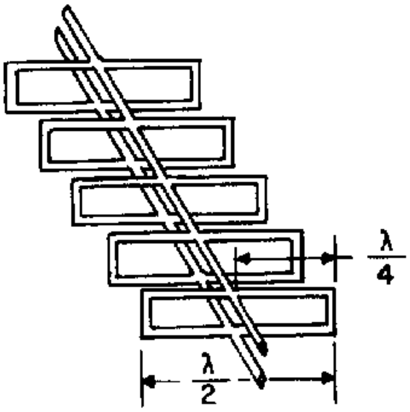


Figure 1-7.—Metallic insulators on each side of a two-wire line.

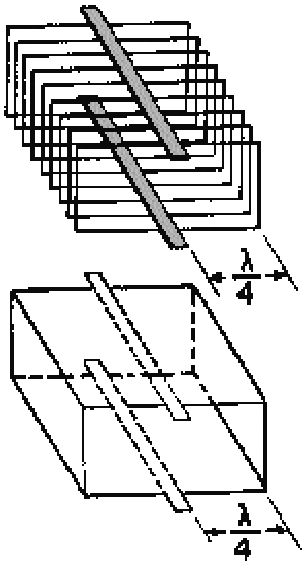


Figure 1-8.—Forming a waveguide by adding quarter-wave sections.

The comparison of the way electromagnetic fields work on a transmission line and in a waveguide is not exact. During the change from a two-wire line to a waveguide, the electromagnetic field configurations also undergo many changes. These will be discussed later in this chapter. As a result of these changes, the waveguide does not actually operate like a two-wire line that is completely shunted by quarter-wave sections. If it did, the use of a waveguide would be limited to a single-frequency wavelength that was four times the length of the quarter-wave sections. In fact, waves of this length cannot pass efficiently through waveguides. Only a small range of frequencies of somewhat shorter wavelength (higher frequency) can pass efficiently.

As shown in figure 1-9, the widest dimension of a waveguide is called the "a" dimension and determines the range of operating frequencies. The narrowest dimension determines the power-handling capability of the waveguide and is called the "b" dimension.

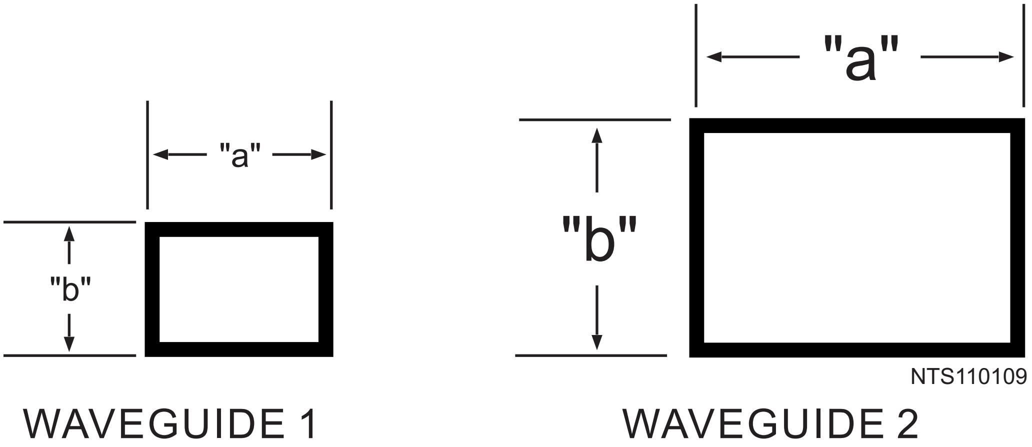


Figure 1-9.—Labeling waveguide dimensions.

NOTE

This method of labeling waveguides is not standard in all texts. Different methods may be used in other texts on microwave principles, but this method is in accordance with Navy Military Standards (MIL-STDS).

The ability of a waveguide of a given dimension to transport more than one frequency may be better understood by analyzing the actions illustrated in figure 1-10A, B, and C. A waveguide may be considered as having upper and lower quarter-wave sections and a central section which is a solid conductor called a BUS BAR. In figure 1-10A, distance mn is equal to distance pq, and both are equal to one quarter-wavelength (λ/4).

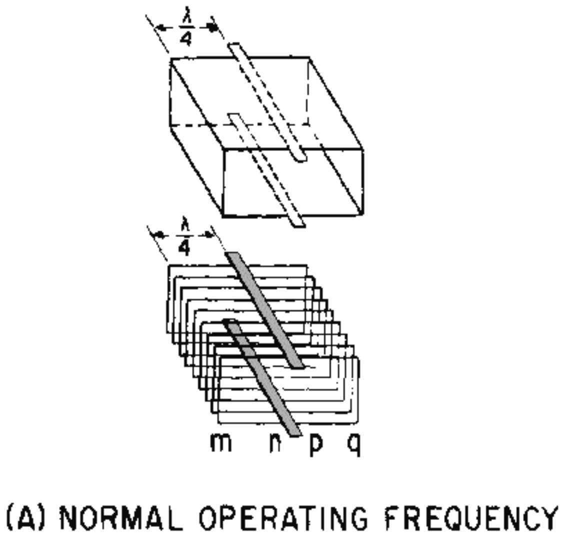


Figure 1-10A.—Frequency effects on a waveguide. NORMAL OPERATING FREQUENCY.

NOTE

Throughout *NEETS*, 1/4λ and λ/4 are both used to represent one quarter-wavelength and are used interchangeably. Also, λ/2 and 3/2λ will be used to represent one half-wavelength and 1 1/2 wavelengths, respectively.

Distance np is the width of the bus bar. If the overall dimensions of the waveguide are held constant, the required length of the quarter-wave sections DECREASES as the frequency increases. As illustrated in figure 1-10B, this causes the width of the bus bar to INCREASE. In theory the waveguide could function at an infinite number of frequencies higher than the designed frequency; as the length of each quarter-wave section approaches zero, the bus bar continues to widen to fill the available space. However, in practice, an upper frequency limit is caused by modes of operation, which will be discussed later.

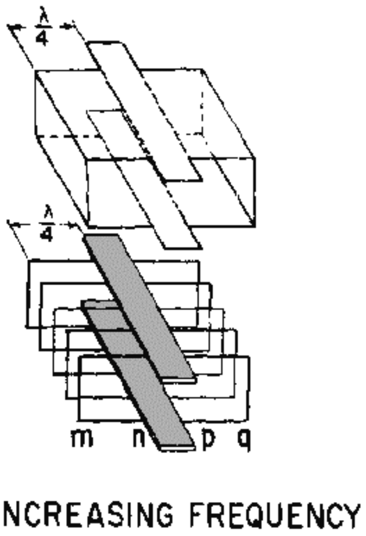


Figure 1-10B.—Frequency effects on a waveguide. INCREASING FREQUENCY.

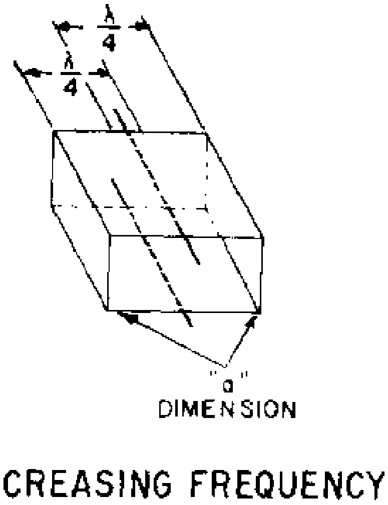


Figure 1-10C.—Frequency effects on a waveguide. DECREASING FREQUENCY.

If the frequency of a signal is decreased so much that two quarter-wavelengths are longer than the wide dimension of a waveguide, energy will no longer pass through the waveguide. This is the lower frequency limit, or CUT-OFF FREQUENCY, of a given waveguide. In practical applications, the wide dimension of a waveguide is usually 0.7 wavelength at the operating frequency. This allows the waveguide to handle a small range of frequencies both above and below the operating frequency. The "b" dimension is governed by the breakdown potential of the dielectric, which is usually air. Dimensions ranging from 0.2 to 0.5 wavelength are common for the "b" sides of a waveguide.

Q-9. At very high frequencies, what characteristics are displayed by ordinary insulators?

Q-10. What type of insulator works well at very high frequencies?

Q-11. The frequency range of a waveguide is determined by what dimensison?

Q-12. What happens to the bus bar dimensions of the waveguide when the frequency is increased?

Q-13. When the frequency is decreased so that two quarter-wavelengths are longer than the "a" (wide) dimension of the waveguide, what will happen?

Energy Propagation in Waveguides

Since energy is transferred through waveguides by electromagnetic fields, you need a basic understanding of field theory. Both magnetic (H FIELD) and electric field (E FIELD) are present in waveguides, and the interaction of these fields causes energy to travel through the waveguide. This action is best understood by first looking at the properties of the two individual fields.

E FIELD.—An electric field exists when a difference of potential causes a stress in the dielectric between two points. The simplest electric field is one that forms between the plates of a capacitor when one plate is made positive compared to the other, as shown in figure 1-11A. The stress created in the dielectric is an electric field.

Electric fields are represented by arrows that point from the positive toward the negative potential. The number of arrows shows the relative strength of the field. In figure 1-11A, for example, evenly spaced arrows indicate the field is evenly distributed. For ease of explanation, the electric field is abbreviated E field, and the lines of stress are called E lines.

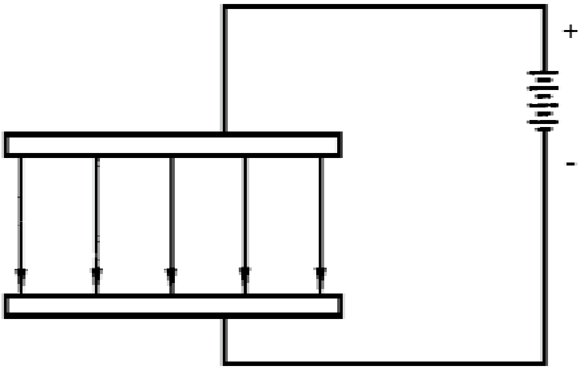


Figure 1-11A.—Simple electric fields. CAPACITOR.

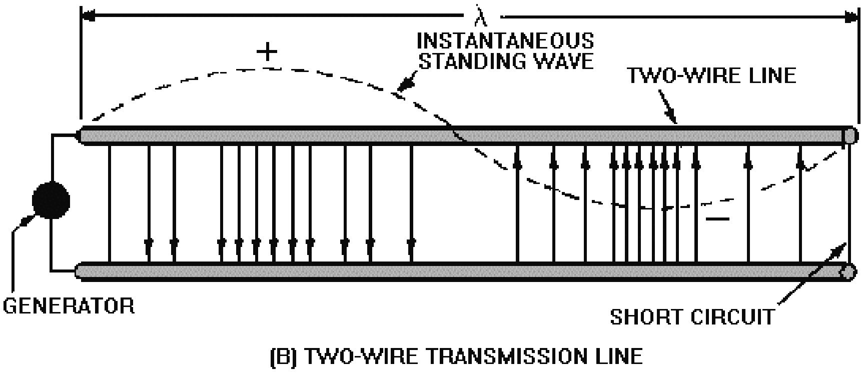


Figure 1-11B—Simple electric fields. TWO-WIRE TRANSMISSION LINE.

The two-wire transmission line, illustrated in figure 1-11B, has an instantaneous standing wave of voltage applied to it by the generator. The line is short-circuited at one-wavelength, at the positive and negative voltage peaks, but the arrows, representing each field, point in opposite directions. The voltage across the line varies sinusoidally. Therefore, the density of the E-lines varies sinusoidally.

The development of the E field in a waveguide can be illustrated by a two-wire transmission line separated by several, double quarter-wave sections, called half-wave frames, as illustrated in figure 1-12. As shown, the voltage across the two-wire line varies in a sine-wave pattern and the density of the E field also varies in a sine-wave pattern. The half-wave frames located at high-voltage points (1) and (3) have a strong E field. The frames at the zero-voltage points (2) have no E fields present. Frame (4) has a weak E field and is located at a point between maximum and minimum voltage. This illustration is a buildup to the three-dimensional aspect of the full E field in a waveguide.

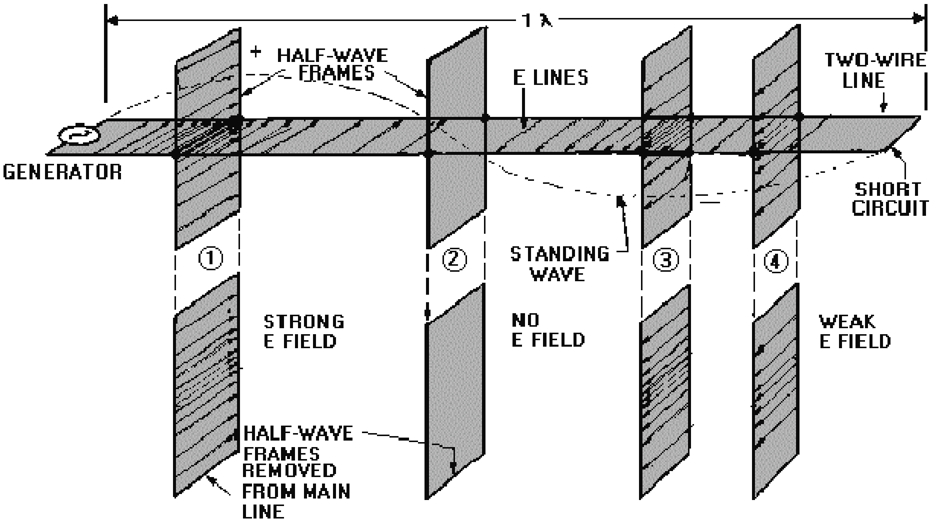


Figure 1-12.—E fields on a two-wire line with half-wave frames.

Figure 1-13, view (A), shows the E-field pattern created by a voltage sine wave applied to a one-wavelength section of waveguide shorted at one end. The electric fields are represented by the arrows shown in views (B) and (C). In the top view of view (A), the tip of each arrow is represented by a dot and the tail of each arrow is represented by an X. The E field varies in density at the same sine-wave rate as the applied voltage. This illustration represents the instant that the applied voltage wave is at its peak. At other times, the voltage and the E field in the waveguide vary continuously from zero to the peak value. Voltage and E-field polarity reverse with every reversal of the input. Note that the end view shown in view (B) shows the E field is maximum at the center and minimum near the walls of the waveguide. View (C) shows the arrangement of electromagnetic fields within a three-dimensional waveguide.

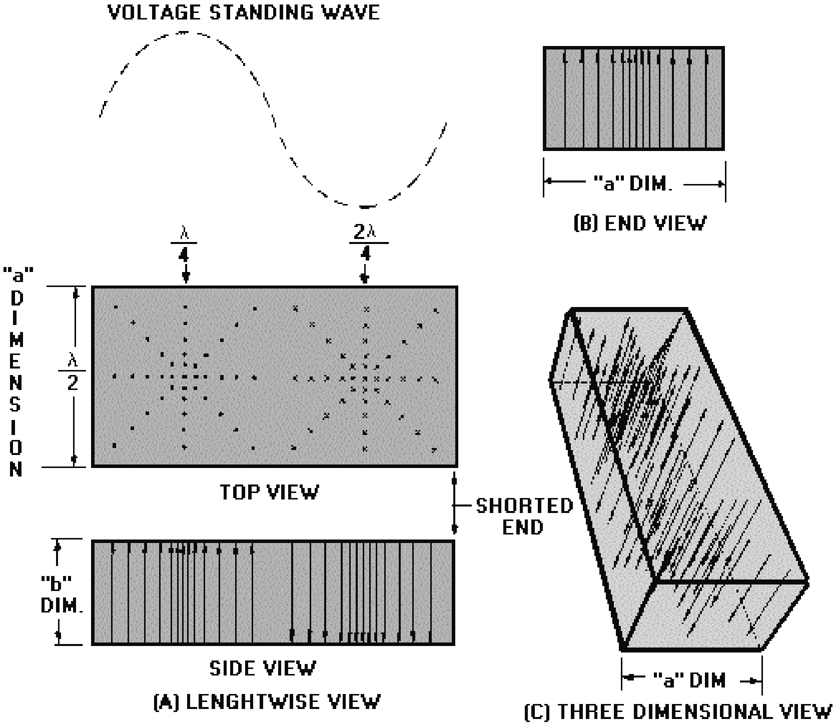


Figure 1-13.—E field of a voltage standing wave across a 1-wavelength section of a waveguide.

H FIELD.—The magnetic field in a waveguide is made up of magnetic lines of force that are caused by current flow through the conductive material of the waveguide. Magnetic lines of force, called H lines, are continuous closed loops, as shown in figure 1-14. All of the H lines associated with current are collectively called a magnetic field or H field. The strength of the H field, indicated by the number of H lines in a given area, varies directly with the amount of current.

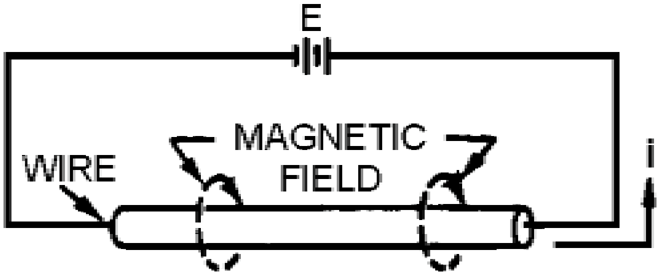


Figure 1-14.—Magnetic field on a single wire.

Although H lines encircle a single, straight wire, they behave differently when the wire is formed into a coil, as shown in figure 1-15. In a coil the individual H lines tend to form around each turn of wire. Since the H lines take opposite directions between adjacent turns, the field between the turns is cancelled. Inside and outside the coil, where the direction of each H field is the same, the fields join and form continuous H lines around the entire coil.

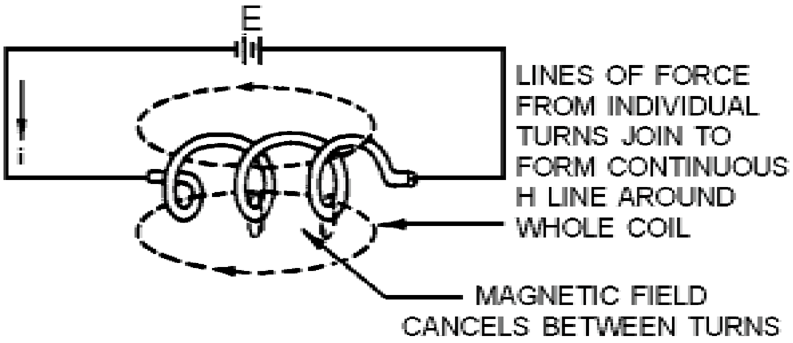


Figure 1-15.—Magnetic field on a coil.

A similar action takes place in a waveguide. In figure 1-16A, a two-wire line with quarter-wave sections is shown. Currents flow in the main line and in the quarter-wave sections. The current direction produces the individual H lines around each conductor as shown. When a large number of sections exist, the fields cancel between the sections, but the directions are the same both inside and outside the waveguide. At half-wave intervals on the main line, current will flow in opposite directions. This produces H-line loops having opposite directions. In figure 1-16A, current at the left end is opposite to the current at the right end. The individual loops on the main line are opposite in direction. All around the framework they join so that the long loop shown in figure 1-16B is formed. Outside the waveguide the individual loops cannot join to form a continuous loop. Thus, no magnetic field exists outside a waveguide.

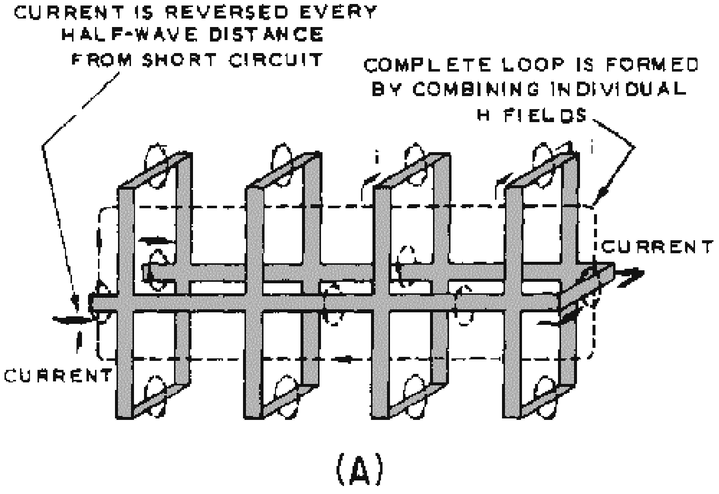


Figure 1-16A.—Magnetic fields on a two-wire line with half-wave frames.

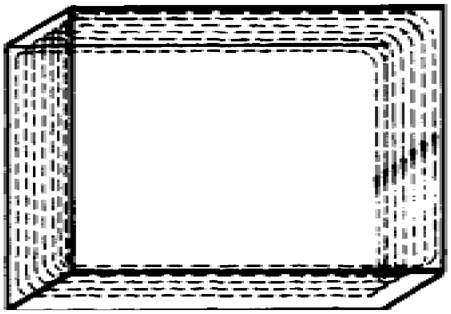


Figure 1-16B.—Magnetic fields on a two-wire line with half-wave frames.

If the two-wire line and the half-wave frames are developed into a waveguide that is closed at both ends (as shown in figure 1-16B), the distribution of H lines will be as shown in figure 1-17. If the waveguide is extended to 1 1/2λ, these H lines form complete loops at half-wave intervals with each group reversed in direction. Again, no H lines can form outside the waveguide as long as it is completely enclosed.

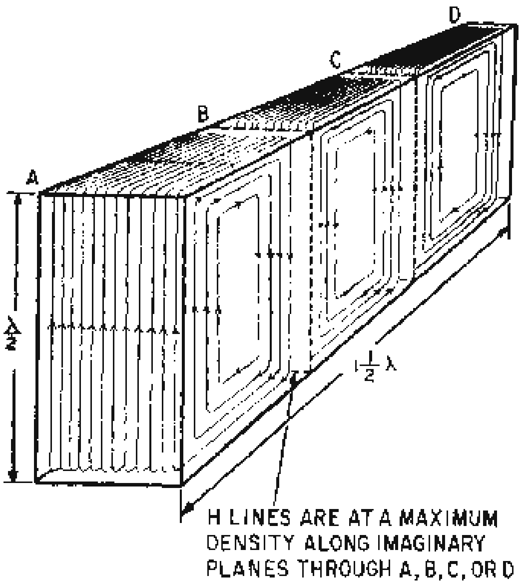
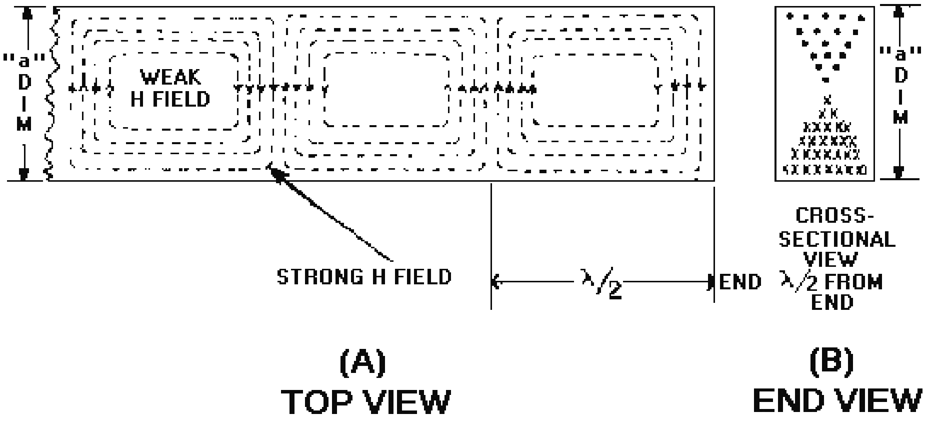


Figure 1-17.—Magnetic field pattern in a waveguide.

Figure 1-18 shows a cross-sectional view of the magnetic field pattern illustrated in figure 1-17. Note in view (A) that the field is strongest at the edges of the waveguide where the current is highest. The minimum field strength occurs at the zero-current points. View (B) shows the field pattern as it appears λ/4 from the end view of the waveguide. As with the previously discussed E fields, the H fields shown in figures 1-17 and 1-18 represent a condition that exists at only one instant in time. During the peak of the next half cycle of the input current, all field directions are reversed and the field will continue to change with changes in the input.



(A) TOP VIEW

(B) END VIEW

Figure 1-18.—Magnetic field in a waveguide three half-wavelengths long.

BOUNDARY CONDITIONS IN A WAVEGUIDE.—The travel of energy down a waveguide is similar, but not identical, to the travel of electromagnetic waves in free space. The difference is that the energy in a waveguide is confined to the physical limits of the guide. Two conditions, known as BOUNDARY CONDITIONS, must be satisfied for energy to travel through a waveguide.

The first boundary condition (illustrated in figure 1-19A) can be stated as follows:

For an electric field to exist at the surface of a conductor it must be perpendicular to the conductor.

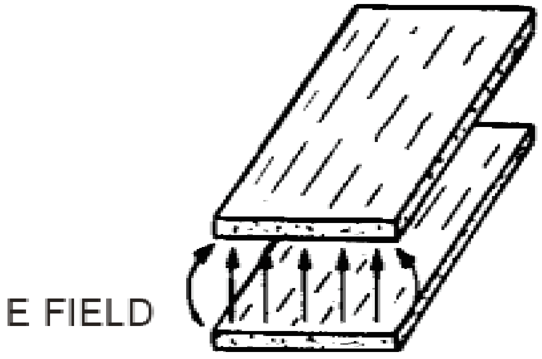


Figure 1-19A.—E field boundary condition. MEETS BOUNDARY CONDITIONS.

The opposite of this boundary condition, shown in figure 1-19B, is also true. An electric field CANNOT exist parallel to a perfect conductor.

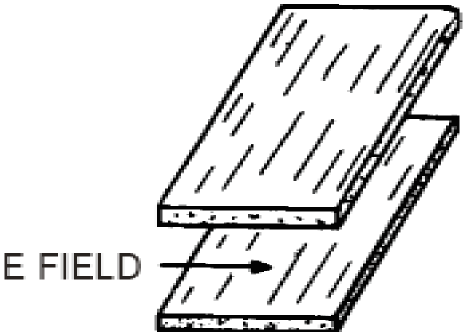


Figure 1-19B.—E field boundary condition. DOES NOT MEET BOUNDARY CONDITIONS.

The second boundary condition, which is illustrated in figure 1-20, can be stated as follows:

For a varying magnetic field to exist, it must form closed loops in parallel with the conductors and be perpendicular to the electric field.

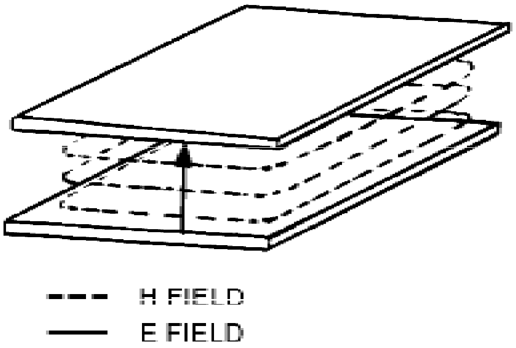


Figure 1-20.—H field boundary condition.

Since an E field causes a current flow that in turn produces an H field, both fields always exist at the same time in a waveguide. If a system satisfies one of these boundary conditions, it must also satisfy the other since neither field can exist alone. You should briefly review the principles of electromagnetic propagation in free space (*NEETS*, Module 10, *Introduction to Wave Propagation, Transmission Lines, and Antennas).* This review will help you understand how a waveguide satisfies the two boundary conditions necessary for energy propagation in a waveguide.

WAVEFRONTS WITHIN A WAVEGUIDE.—Electromagnetic energy transmitted into space consists of electric and magnetic fields that are at right angles (90 degrees) to each other and at right angles to the direction of propagation. A simple analogy to establish this relationship is by use of the right-hand rule for electromagnetic energy, based on the POYNTING VECTOR. It indicates that a screw (right-hand thread) with its axis perpendicular to the electric and magnetic fields will advance in the direction of propagation if the E field is rotated to the right (toward the H field). This rule is illustrated in figure 1-21.

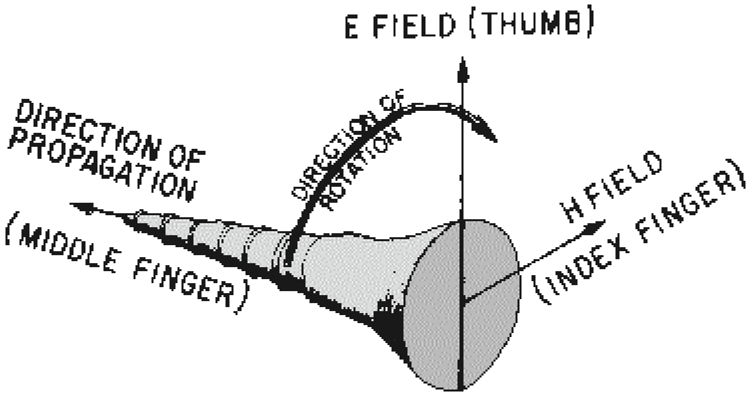


Figure 1-21.—The Poynting vector.

The combined electric and magnetic fields form a wavefront that can be represented by alternate negative and positive peaks at half-wavelength intervals, as illustrated in figure 1-22. Angle θ is the direction of travel of the wave with respect to some reference axis.

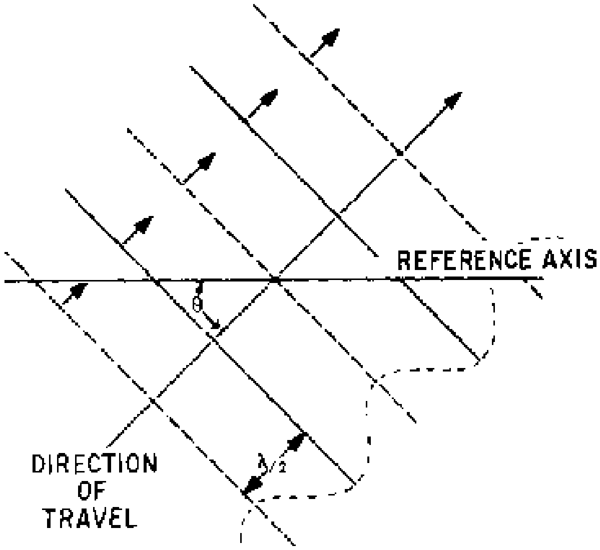


Figure 1-22.—Wavefronts in space.

If a second wavefront, differing only in the direction of travel, is present at the same time, a resultant of the two is formed. The resultant is illustrated in figure 1-23, and a close inspection reveals important characteristics of combined wavefronts. Both wavefronts add at all points on the reference axis and cancel at half-wavelength intervals from the reference axis. Therefore, alternate additions and cancellations of the two wavefronts occur at progressive half-wavelength increments from the reference axis. In figure 1-23, the lines labeled A, C, F, and H are addition points, and those labeled B, D, E, and G are cancellation points.

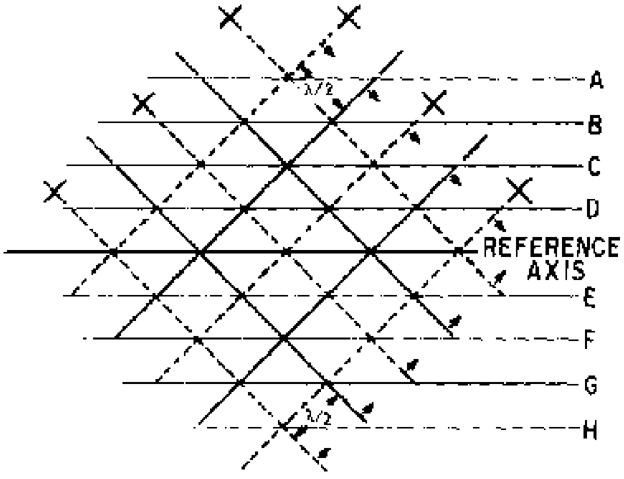


Figure 1-23.—Combined wavefronts.

If two conductive plates are placed along cancellation lines D and E or cancellation lines B and G, the first boundary condition for waveguides will be satisfied; that is, the E fields will be zero at the surface of the conductive plates. The second boundary condition is, therefore, automatically satisfied. Since these plates serve the same purpose as the "b" dimension walls of a waveguide, the "a" dimension walls can be added without affecting the magnetic or electric fields.

When a quarter-wavelength probe is inserted into a waveguide and supplied with microwave energy, it will act as a quarter-wave vertical antenna. Positive and negative wavefronts will be radiated, as shown in figure 1-24. Any portion of the wavefront traveling in the direction of arrow C will rapidly decrease to zero because it does not fulfill either of the required boundary conditions. The parts of the wavefronts that travel in the directions of arrows A and B will reflect from the walls and form reverse-phase wavefronts. These two wavefronts, and those that follow, are illustrated in figure 1-25. Notice that the wavefronts crisscross down the center of the waveguide and produce the same resultant field pattern that was shown in figure 1-23.

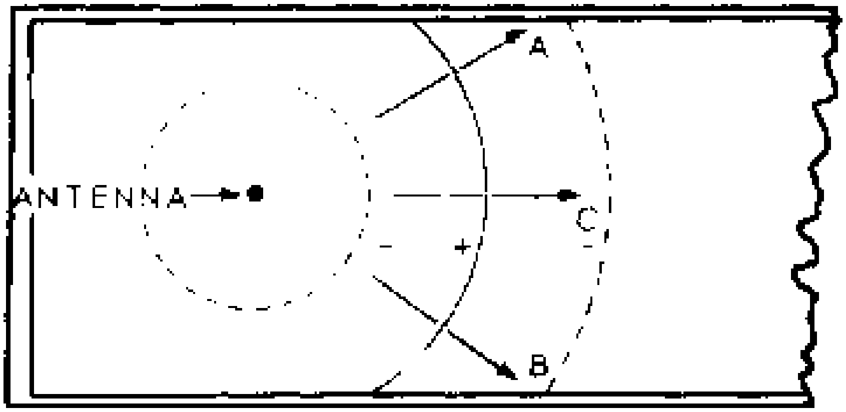
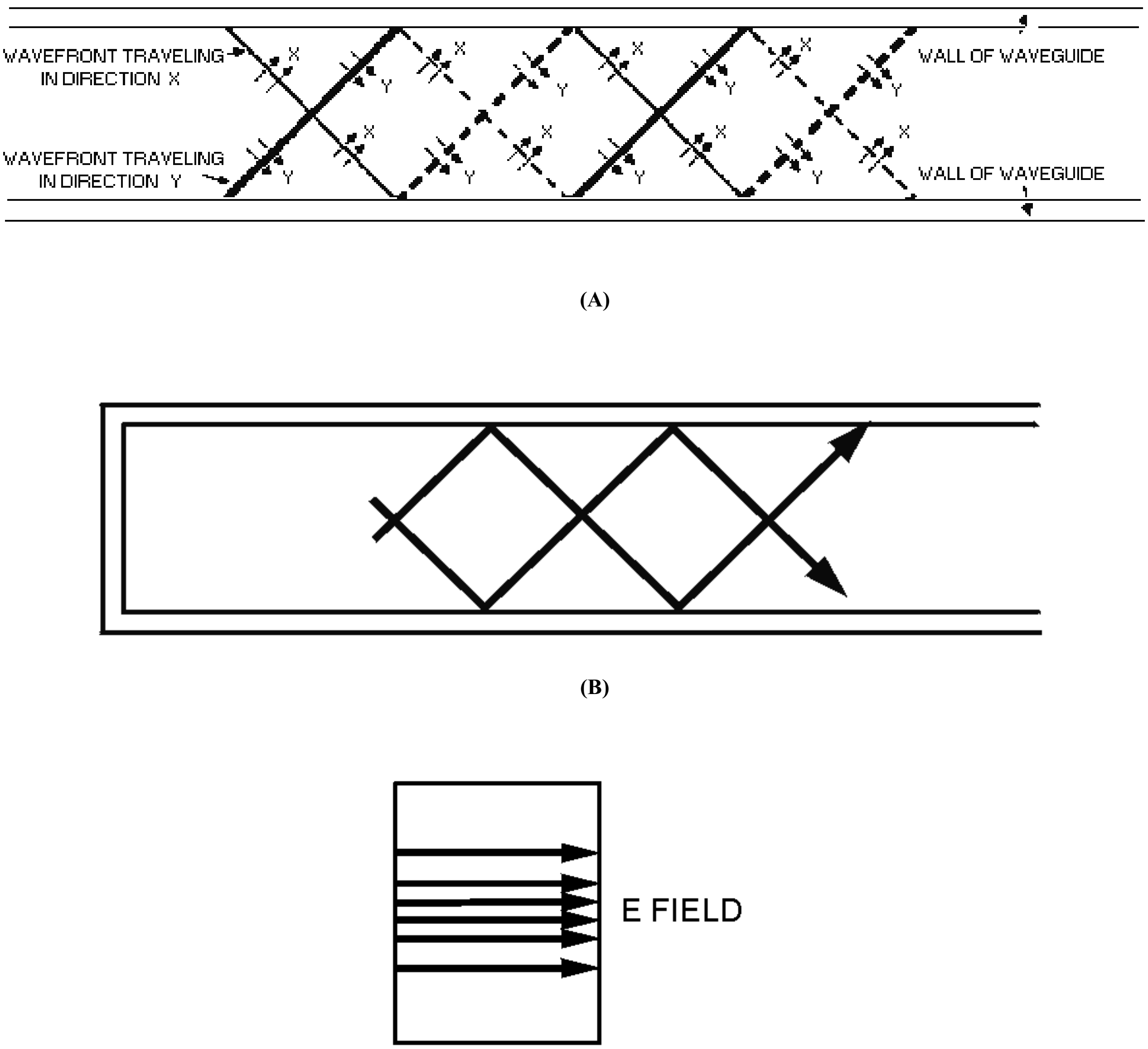


Figure 1-24.—Radiation from probe placed in a waveguide.



(A)

(B)

(C)

Figure 1-25.—Wavefronts in a waveguide.

The reflection of a single wavefront off the "b" wall of a waveguide is shown in figure 1-26. The wavefront is shown in view (A) as small particles. In views (B) and (C) particle 1 strikes the wall and is bounced back from the wall without losing velocity. If the wall is perfectly flat, the angle at which it strikes the wall, known as the angle of incidence (θ), is the same as the angle of reflection (ø) and are measured perpendicular to the waveguide surface. An instant after particle 1 strikes the wall, particle 2 strikes the wall, as shown in view (C), and reflects in the same manner. Because all the particles are traveling at the same velocity, particles 1 and 2 do not change their relative position with respect to each other. Therefore, the reflected wave has the same shape as the original. The remaining particles as shown in views (D), (E) and (F) reflect in the same manner. This process results in a reflected wavefront identical in shape, but opposite in polarity, to the incident wave.

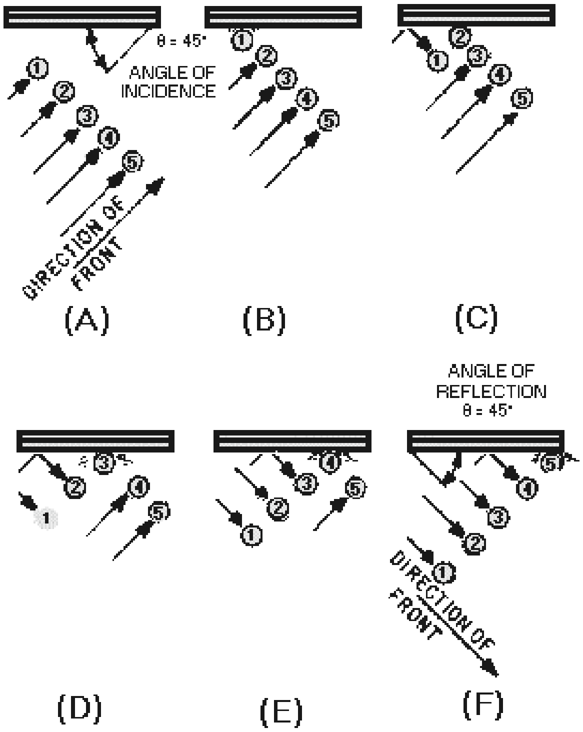


Figure 1-26.—Reflection of a single wavefront.

Figures 1-27A and 1-27B, each illustrate the direction of propagation of two different electromagnetic wavefronts of different frequencies being radiated into a waveguide by a probe. Note that only the direction of propagation is indicated by the lines and arrowheads. The wavefronts are at right angles to the direction of propagation. The angle of incidence (θ) and the angle of reflection (ø) of the wavefronts vary in size with the frequency of the input energy, but the angles of reflection are equal to each other in a waveguide. The CUTOFF FREQUENCY in a waveguide is a frequency that would cause angles of incidence and reflection to be zero degrees. At any frequency below the cutoff frequency, the wavefronts will be reflected back and forth across the guide (setting up standing waves) and no energy will be conducted down the waveguide.

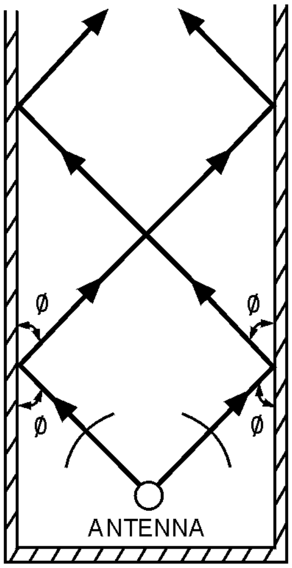


Figure 1-27A.—Different frequencies in a waveguide.

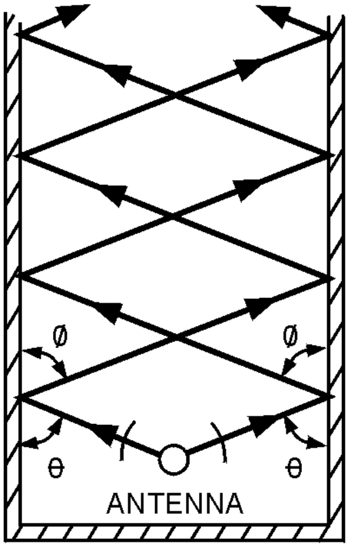


Figure 1-27B.—Different frequencies in a waveguide.

The velocity of propagation of a wave along a waveguide is less than its velocity through free space (speed of light). This lower velocity is caused by the zigzag path taken by the wavefront. The forward-progress velocity of the wavefront in a waveguide is called GROUP VELOCITY and is somewhat slower than the speed of light.

The group velocity of energy in a waveguide is determined by the reflection angle of the wavefronts off the "b" walls. The reflection angle is determined by the frequency of the input energy. This basic principle is illustrated in figures 1-28A, 1-28B, and 1-28C. As frequency is decreased, the reflection angle decreases causing the group velocity to decrease. The opposite is also true; increasing frequency increases the group velocity.

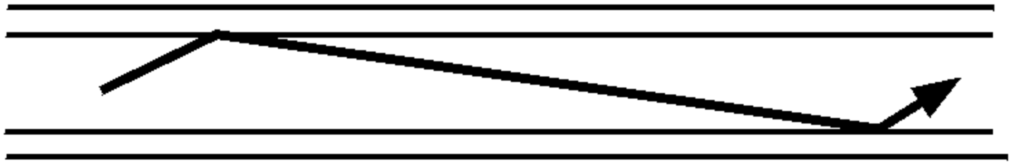


Figure 1-28A.—Reflection angle at various frequencies. LOW FREQUENCY.

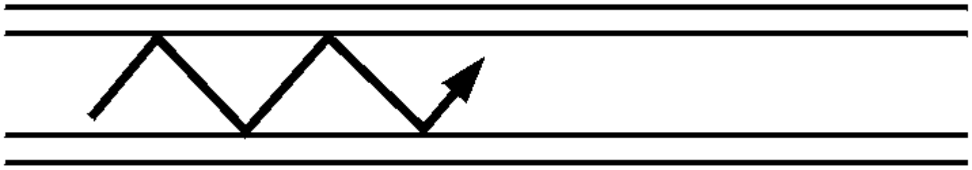


Figure 1-28B.—Reflection angle at various frequencies. MEDIUM FREQUENCY.

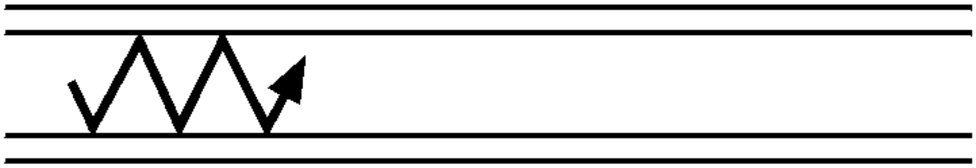


Figure 1-28C.—Reflection angle at various frequencies. HIGH FREQUENCY.

Q-14. What interaction causes energy to travel down a waveguide?

Q-15. What is indicated by the number of arrows (closeness of spacing) used to represent an electric field?

Q-16. What primary condition must magnetic lines of force meet in order to exist?

Q-17. What happens to the H lines between the conductors of a coil when the conductors are close together?

Q-18. For an electric field to exist at the surface of a conductor, the field must have what angular relationship to the conductor?

Q-19. When a wavefront is radiated into a waveguide, what happens to the portions of the wavefront that do not satisfy the boundary conditions?

Q-20. Assuming the wall of a waveguide is perfectly flat, what is the angular relationship between the angle of incidence and the angle of reflection?

Q-21. What is the frequency called that produces angles of incidence and reflection that are perpendicular to the waveguide walls?

Q-22. Compared to the velocity of propagation of waves in air, what is the velocity of propagation of waves in waveguides?

Q-23. What term is used to identify the forward progress velocity of wavefronts in a waveguide?

Waveguide Modes of Operation

The waveguide analyzed in the previous paragraphs yields an electric field configuration known as the half-sine electric distribution. This configuration, called a MODE OF OPERATION, is shown in figure 1-29. Recall that the strength of the field is indicated by the spacing of the lines; that is, the closer the lines, the stronger the field. The regions of maximum voltage in this field move continuously down the waveguide in a sine-wave pattern. To meet boundary conditions, the field must always be zero at the "b" walls.

The half-sine field is only one of many field configurations, or modes, that can exist in a rectangular waveguide. A full-sine field can also exist in a rectangular waveguide because, as shown in figure 1-30, the field is zero at the "b" walls.

Similarly, a 1 1/2 sine-wave field can exist in a rectangular waveguide because this field also meets the boundary conditions. As shown in figure 1-31, the field is perpendicular to any conducting surface it touches and is zero along the "b" walls.

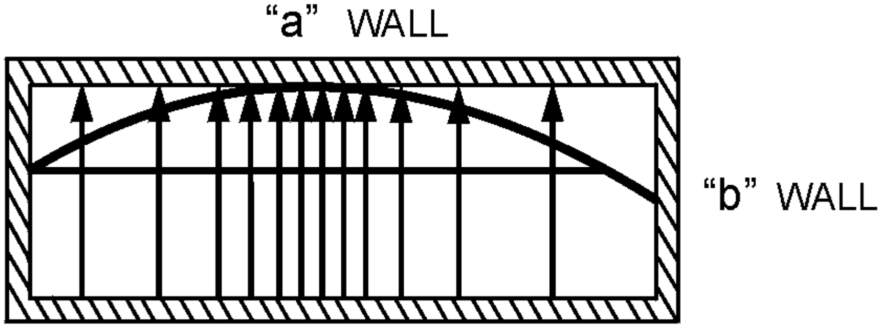


Figure 1-29.—Half-sine E field distribution.

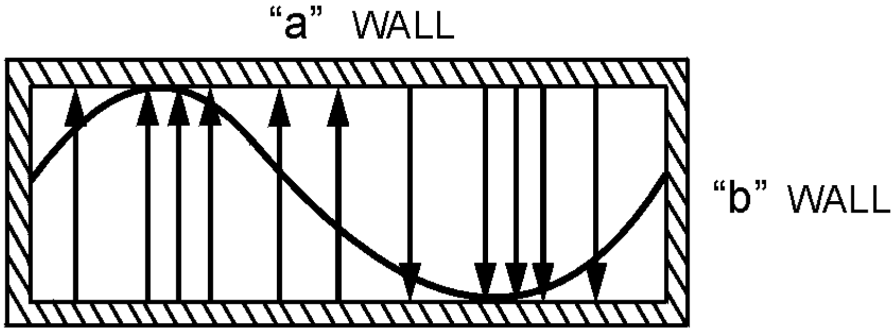


Figure 1-30.—Full-sine E field distribution.

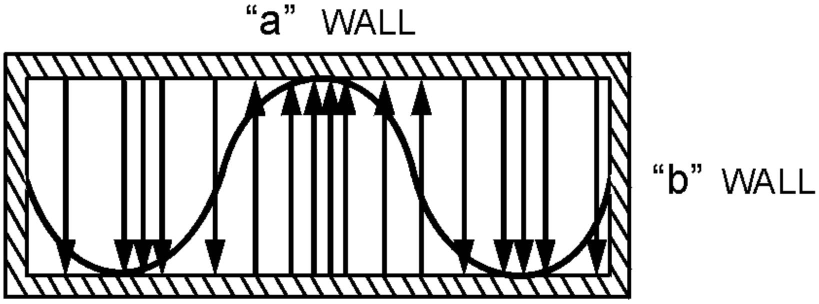


Figure 1-31.—One and one-half sine E field distribution.

The magnetic field in a rectangular waveguide is in the form of closed loops parallel to the surface of the conductors. The strength of the magnetic field is proportional to the electric field. Figure 1-32 illustrates the magnetic field pattern associated with a half-sine electric field distribution. The magnitude of the magnetic field varies in a sine-wave pattern down the center of the waveguide in "time phase" with the electric field. TIME PHASE means that the peak H lines and peak E lines occur at the same instant in time, although not necessarily at the same point along the length of the waveguide.

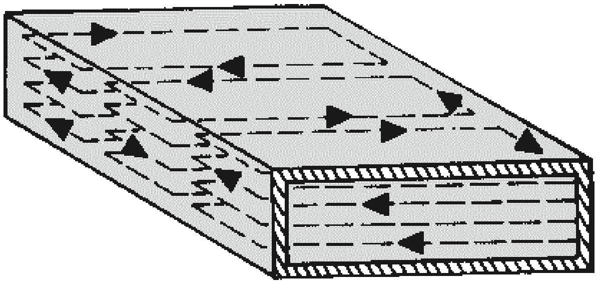


Figure 1-32.—Magnetic field caused by a half-sine E field.

An electric field in a sine-wave pattern also exists down the center of a waveguide. In figure 1-33, view (A), consider the two wavefronts, C and D. Assume that they are positive at point 1 and negative at point 2. When the wavefronts cross at points 1 and 2, each field is at its maximum strength. At these points, the fields combine, further increasing their strength. This action is continuous because each wave is always followed by a replacement wave. Figure 1-33, view (B), illustrates the resultant sine configuration of the electric field at the center of the waveguide. This configuration is only one of the many field patterns that can exist in a waveguide. Each configuration forms a separate mode of operation. The easiest mode to produce is called the DOMINANT MODE. Other modes with different field configurations may occur accidentally or may be caused deliberately.

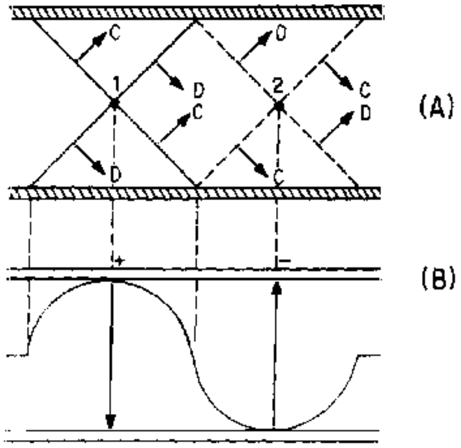


Figure 1-33.—Crisscrossing wavefronts and the resultant E field.

The dominant mode is the most efficient mode. Waveguides are normally designed so that only the dominant mode will be used. To operate in the dominant mode, a waveguide must have an "a" (wide) dimension of at least one half-wavelength of the frequency to be propagated. The "a" dimension of the waveguide must be kept near the minimum allowable value to ensure that only the dominant mode will exist. In practice, this dimension is usually 0.7 wavelength.

Of the possible modes of operation available for a given waveguide, the dominant mode has the lowest cutoff frequency. The high-frequency limit of a rectangular waveguide is a frequency at which its "a" dimension becomes large enough to allow operation in a mode higher than that for which the waveguide has been designed.

Waveguides may be designed to operate in a mode other than the dominant mode. An example of a full-sine configuration mode is shown in figures 1-34A and 1-34B. The "a" dimension of the waveguide in this figure is one wavelength long. You may assume that the two-wire line is 1/4λ from one of the "b" walls, as shown in figure 1-34A. The remaining distance to the other "b" wall is 3/4λ. The three-quarter wavelength section has the same high impedance as the quarter-wave section; therefore, the two-wire line is properly insulated. The field configuration shows a complete sine-wave pattern across the "a" dimension, as illustrated in figure 1-34B.

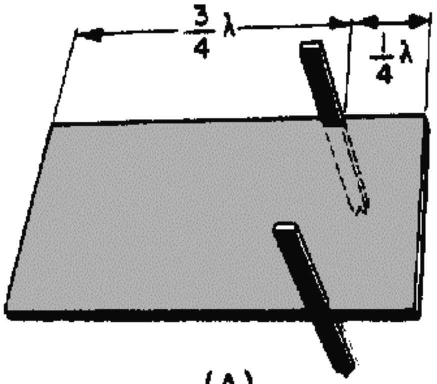


Figure 1-34A.—Waveguide operation in other than dominant mode.

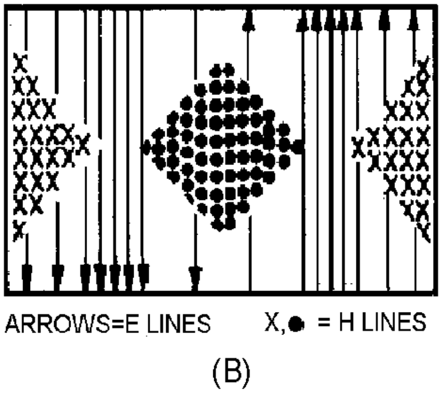


Figure 1-34B.—Waveguide operation in other than dominant mode.

Circular waveguides are used in specific areas of radar and communications systems, such as rotating joints used at the mechanical point where the antennas rotate. Figure 1-35 illustrates the dominant mode of a circular waveguide. The cutoff wavelength of a circular guide is 1.71 times the diameter of the waveguide. Since the "a" dimension of a rectangular waveguide is approximately one half-wavelength at the cutoff frequency, the diameter of an equivalent circular waveguide must be 2 ÷ 1.71, or approximately 1.17 times the "a" dimension of a rectangular waveguide.

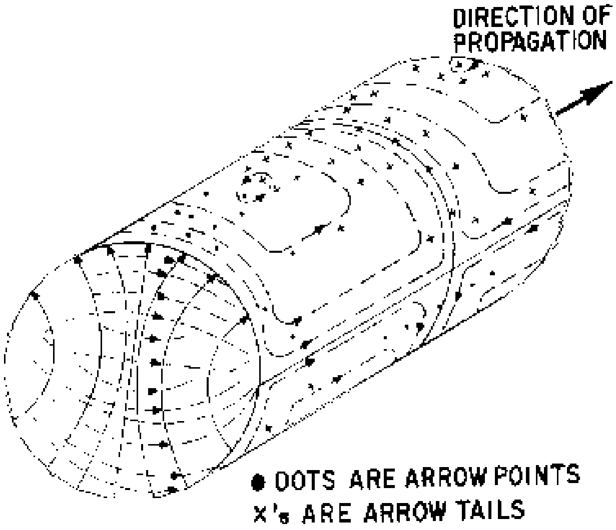


Figure 1-35.—Dominant mode in a circular waveguide.

MODE NUMBERING SYSTEMS.—So far, only the most basic types of E and H field arrangements have been shown. More complicated arrangements are often necessary to make possible coupling, isolation, or other types of operation. The field arrangements of the various modes of operation are divided into two categories: TRANSVERSE ELECTRIC (TE) and TRANSVERSE MAGNETIC (TM).

In the transverse electric (TE) mode, the entire electric field is in the transverse plane, which is perpendicular to the length of the waveguide (direction of energy travel). Part of the magnetic field is parallel to the length axis.

In the transverse magnetic (TM) mode, the entire magnetic field is in the transverse plane and has no portion parallel to the length axis.

Since there are several TE and TM modes, subscripts are used to complete the description of the field pattern. In rectangular waveguides, the first subscript indicates the number of half-wave patterns in the "a" dimension, and the second subscript indicates the number of half-wave patterns in the "b" dimension.

The dominant mode for rectangular waveguides is shown in figure 1-36. It is designated as the TE mode because the E fields are perpendicular to the "a" walls. The first subscript is 1 since there is only one half-wave pattern across the "a" dimension. There are no E-field patterns across the "b" dimension, so the second subscript is 0. The complete mode description of the dominant mode in rectangular waveguides is $TE_{1,0}$. Subsequent descriptions of waveguide operation in this text will assume the dominant ($TE_{1,0}$) mode unless otherwise noted.

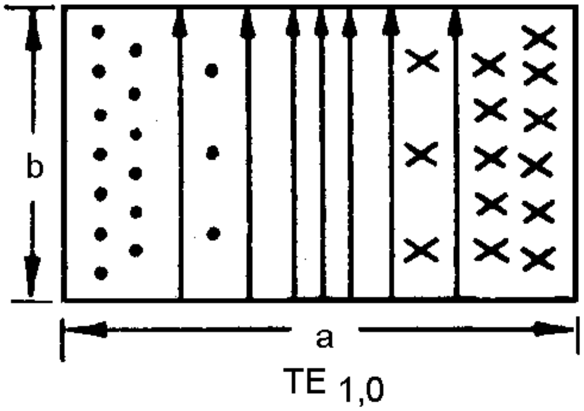


Figure 1-36.—Dominant mode in a rectangular waveguide.

A similar system is used to identify the modes of circular waveguides. The general classification of TE and TM is true for both circular and rectangular waveguides. In circular waveguides the subscripts have a different meaning. The first subscript indicates the number of full-wave patterns around the circumference of the waveguide. The second subscript indicates the number of half-wave patterns across the diameter.

In the circular waveguide in figure 1-37, the E field is perpendicular to the length of the waveguide with no E lines parallel to the direction of propagation. Thus, it must be classified as operating in the TE mode. If you follow the E line pattern in a counterclockwise direction starting at the top, the E lines go from zero, through maximum positive (tail of arrows), back to zero, through maximum negative (head of arrows), and then back to zero again. This is one full wave, so the first subscript is 1. Along the diameter, the E lines go from zero through maximum and back to zero, making a half-wave variation. The second subscript, therefore, is also 1. $TE_{1,1}$ is the complete mode description of the dominant mode in circular waveguides. Several modes are possible in both circular and rectangular waveguides. Figure 1-38 illustrates several different modes that can be used to verify the mode numbering system.

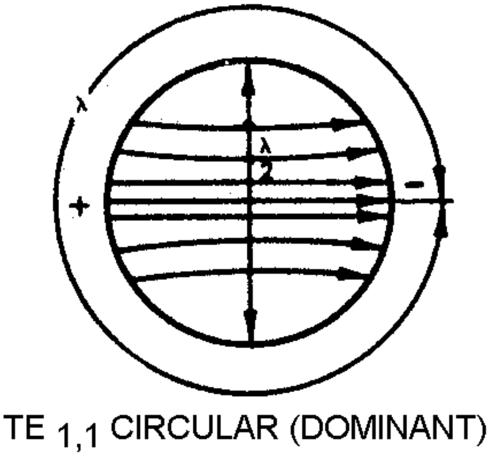


Figure 1-37.—Counting wavelengths in a circular waveguide.

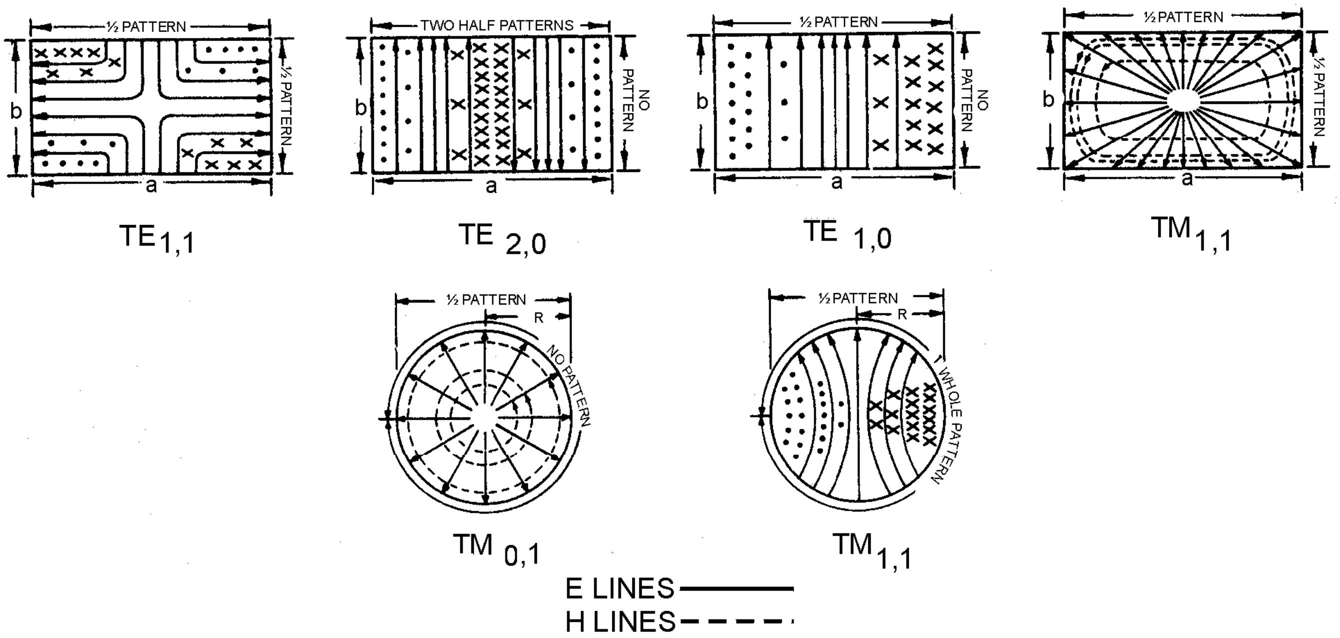


Figure 1-38.—Various modes of operation for rectangular and circular waveguides.

Waveguide Input/Output Methods

A waveguide, as explained earlier in this chapter, operates differently from an ordinary transmission line. Therefore, special devices must be used to put energy into a waveguide at one end and remove it from the other end.

The three devices used to inject or remove energy from waveguides are PROBES, LOOPS, and SLOTS. Slots may also be called APERTURES or WINDOWS.

As previously discussed, when a small probe is inserted into a waveguide and supplied with microwave energy, it acts as a quarter-wave antenna. Current flows in the probe and sets up an E field such as the one shown in figure 1-39A. The E lines detach themselves from the probe. When the probe is located at the point of highest efficiency, the E lines set up an E field of considerable intensity.

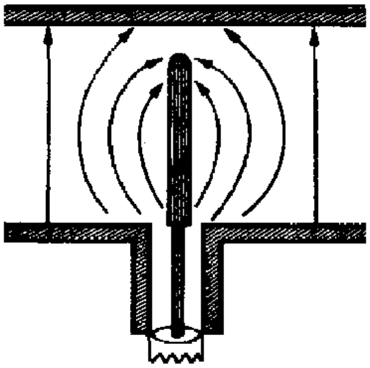


Figure 1-39A.—Probe coupling in a rectangular waveguide.

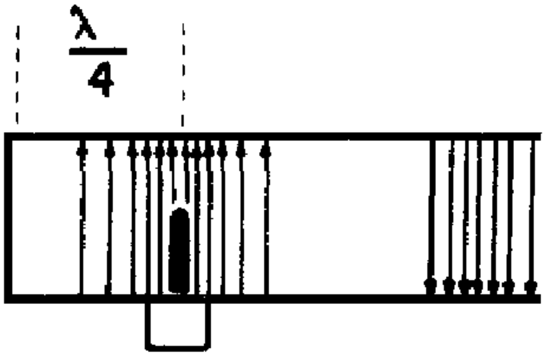


Figure 1-39B.—Probe coupling in a rectangular waveguide.

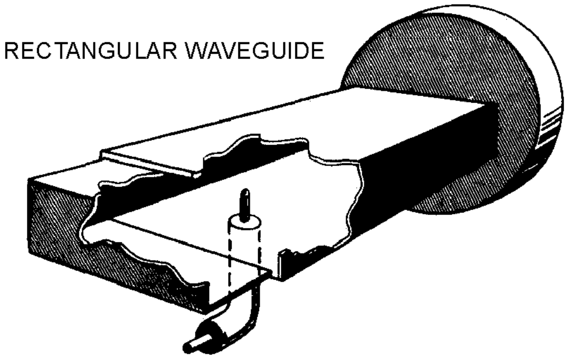


Figure 1-39C.—Probe coupling in a rectangular waveguide.

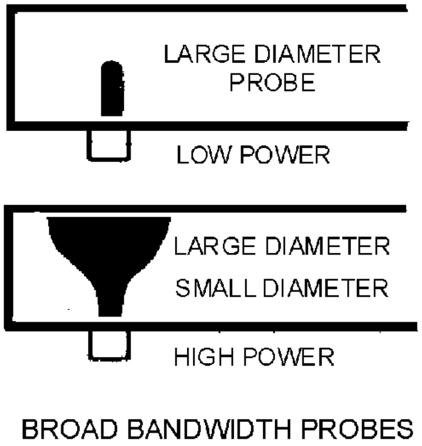


Figure 1-39D.—Probe coupling in a rectangular waveguide.

The most efficient place to locate the probe is in the center of the "a" wall, parallel to the "b" wall, and one quarter-wavelength from the shorted end of the waveguide, as shown in figure 1-39B, and figure 1-39C. This is the point at which the E field is maximum in the dominant mode. Therefore, energy transfer (coupling) is maximum at this point. Note that the quarter-wavelength spacing is at the frequency required to propagate the dominant mode.

In many applications a lesser degree of energy transfer, called loose coupling, is desirable. The amount of energy transfer can be reduced by decreasing the length of the probe, by moving it out of the center of the E field, or by shielding it. Where the degree of coupling must be varied frequently, the probe is made retractable so the length can be easily changed.

The size and shape of the probe determines its frequency, bandwidth, and power-handling capability. As the diameter of a probe increases, the bandwidth increases. A probe similar in shape to a door knob is capable of handling much higher power and a larger bandwidth than a conventional probe. The greater power-handling capability is directly related to the increased surface area. Two examples of broad-bandwidth probes are illustrated in figure 1-39D. Removal of energy from a waveguide is simply a reversal of the injection process using the same type of probe.

Another way of injecting energy into a waveguide is by setting up an H field in the waveguide. This can be accomplished by inserting a small loop which carries a high current into the waveguide, as shown in figure 1-40A. A magnetic field builds up around the loop and expands to fit the waveguide, as shown in figure 1-40B. If the frequency of the current in the loop is within the bandwidth of the waveguide, energy will be transferred to the waveguide.

For the most efficient coupling to the waveguide, the loop is inserted at one of several points where the magnetic field will be of greatest strength. Four of those points are shown in figure 1-40C.

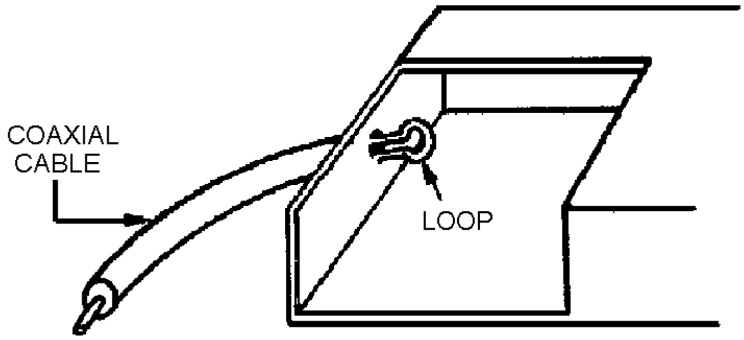


Figure 1-40A.—Loop coupling in a rectangular waveguide.

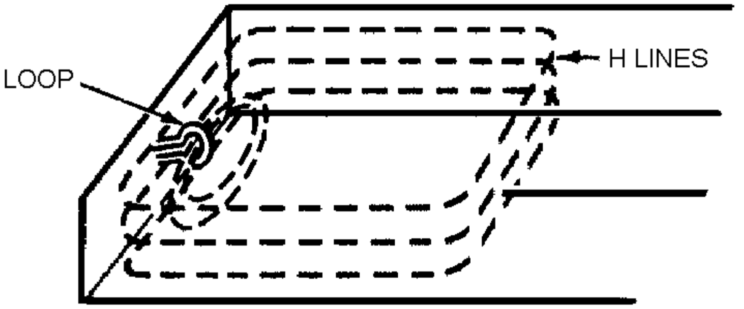


Figure 1-40B.—Loop coupling in a rectangular waveguide.

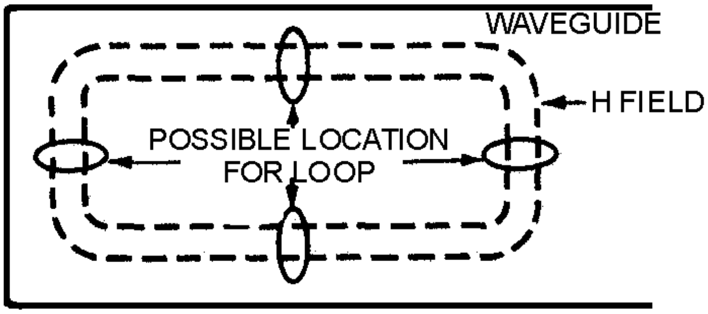


Figure 1-40C.—Loop coupling in a rectangular waveguide.

When less efficient coupling is desired, you can rotate or move the loop until it encircles a smaller number of H lines. When the diameter of the loop is increased, its power-handling capability also increases. The bandwidth can be increased by increasing the size of the wire used to make the loop.

When a loop is introduced into a waveguide in which an H field is present, a current is induced in the loop. When this condition exists, energy is removed from the waveguide.

Slots or apertures are sometimes used when very loose (inefficient) coupling is desired, as shown in figure 1-41. In this method energy enters through a small slot in the waveguide and the E field expands into the waveguide. The E lines expand first across the slot and then across the interior of the waveguide.

Minimum reflections occur when energy is injected or removed if the size of the slot is properly proportioned to the frequency of the energy.

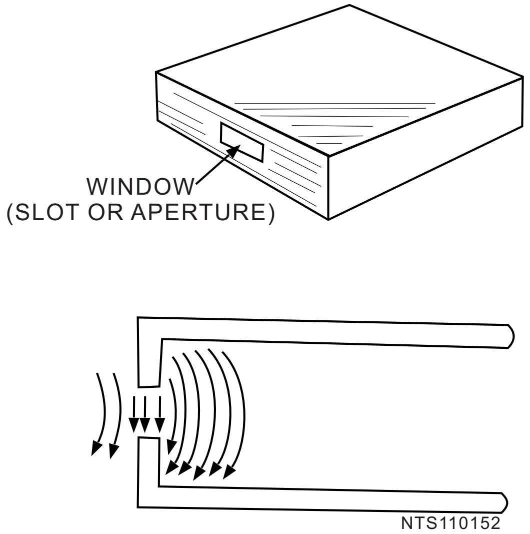


Figure 1-41.—Slot coupling in a waveguide.

After learning how energy is coupled into and out of a waveguide with slots, you might think that leaving the end open is the most simple way of injecting or removing energy in a waveguide. This is not the case, however, because when energy leaves a waveguide, fields form around the end of the waveguide. These fields cause an impedance mismatch which, in turn, causes the development of standing waves and a drastic loss in efficiency. Various methods of impedance matching and terminating waveguides will be covered in the next section.

Q-24. What term is used to identify each of the many field configurations that can exist in waveguides?

Q-25. What field configuration is easiest to produce in a given waveguide?

Q-26. How is the cutoff wavelength of a circular waveguide figured?

Q-27. The field arrangements in waveguides are divided into what two categories to describe the various modes of operation?

Q-28. The electric field is perpendicular to the "a" dimension of a waveguide in what mode?

Q-29. The number of half-wave patterns in the "b" dimension of rectangular waveguides is indicated by which of the two descriptive subscripts?

Q-30. Which subscript, in circular waveguide classification, indicates the number of full-wave patterns around the circumference?

Q-31. What determines the frequency, bandwidth, and power-handling capability of a waveguide probe?

Q-32. Loose or inefficient coupling of energy into or out of a waveguide can be accomplished by the use of what method?

Waveguide Impedance Matching

Waveguide transmission systems are not always perfectly impedance matched to their load devices. The standing waves that result from a mismatch cause a power loss, a reduction in power-handling capability, and an increase in frequency sensitivity. Impedance-changing devices are therefore placed in the waveguide to match the waveguide to the load. These devices are placed near the source of the standing waves.

Figure 1-42 illustrates three devices, called irises, that are used to introduce inductance or capacitance into a waveguide. An iris is nothing more than a metal plate that contains an opening through which the waves may pass. The iris is located in the transverse plane.

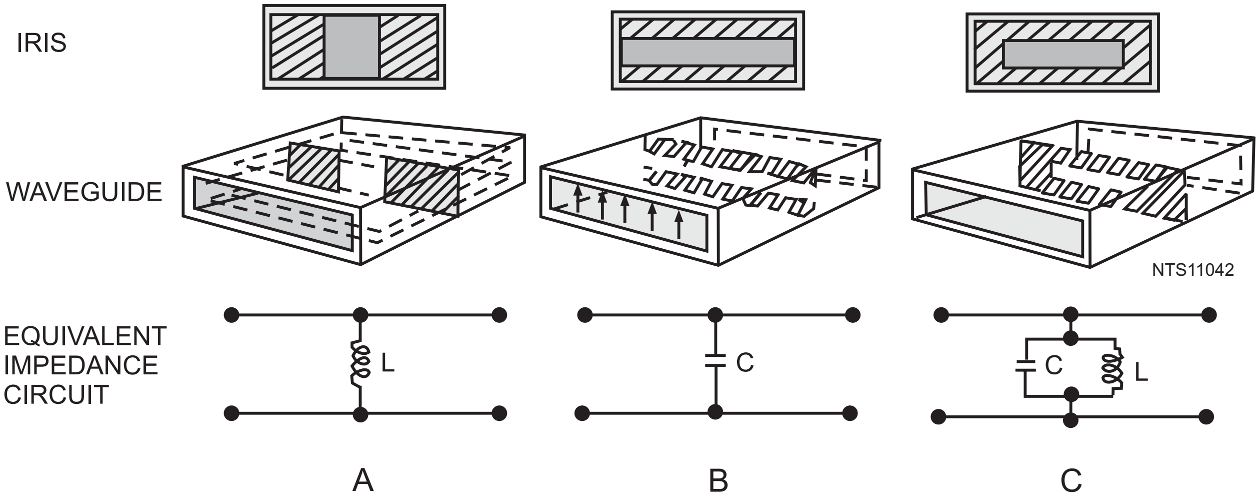


Figure 1-42.—Waveguide irises.

An inductive iris and its equivalent circuit are illustrated in figure 1-42, view (A). The iris places a shunt inductive reactance across the waveguide that is directly proportional to the size of the opening. Notice that the edges of the inductive iris are perpendicular to the magnetic plane. The shunt capacitive reactance, illustrated in view (B), basically acts the same way. Again, the reactance is directly proportional to the size of the opening, but the edges of the iris are perpendicular to the electric plane. The iris, illustrated in view (C), has portions across both the magnetic and electric planes and forms an equivalent parallel-LC circuit across the waveguide. At the resonant frequency, the iris acts as a high shunt resistance. Above or below resonance, the iris acts as a capacitive or inductive reactance.

POSTS and SCREWS made from conductive material can be used for impedance-changing devices in waveguides. Figure 1-43A and 1-43B, illustrate two basic methods of using posts and screws. A post or screw which only partially penetrates into the waveguide acts as a shunt capacitive reactance. When the post or screw extends completely through the waveguide, making contact with the top and bottom walls, it acts as an inductive reactance. Note that when screws are used the amount of reactance can be varied.

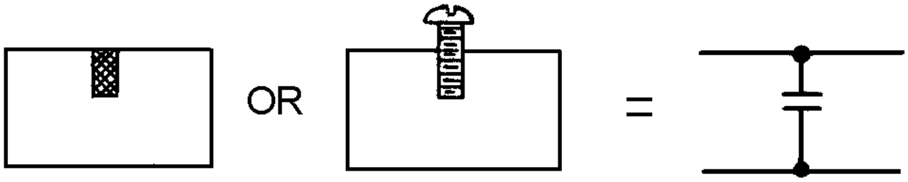


Figure 1-43A.—Conducting posts and screws. PENETRATING.

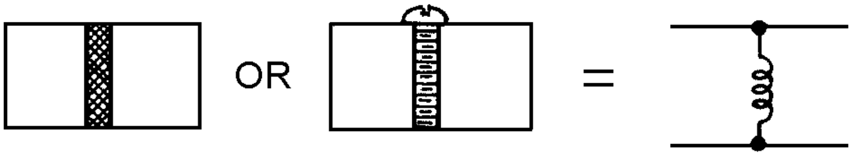


Figure 1-43B.—Conducting posts and screws. EXTENDING THROUGH.

Q-33. What is the result of an impedance mismatch in a waveguide?

Q-34. What is used to construct irises?

Q-35. An iris placed along the "b" dimension wall produces what kind of reactance?

Q-36. How will an iris that has portions along both the "a" and "b" dimension walls act at the resonant frequency?

Waveguide Terminations

Electromagnetic energy is often passed through a waveguide to transfer the energy from a source into space. As previously mentioned, the impedance of a waveguide does not match the impedance of space, and without proper impedance matching, standing waves cause a large decrease in the efficiency of the waveguide.

Any abrupt change in impedance causes standing waves, but when the change in impedance at the end of a waveguide is gradual, almost no standing waves are formed. Gradual changes in impedance can be obtained by terminating the waveguide with a funnel-shaped HORN, such as the three types illustrated in figures 1-44A, 1-44B, and 1-44C. The type of horn used depends upon the frequency and the desired radiation pattern.

Figure 1-44A.—Waveguide horns. E PLANE SECTORAL HORN.

Figure 1-44B.—Waveguide horns. H PLANE SECTORAL HORN.

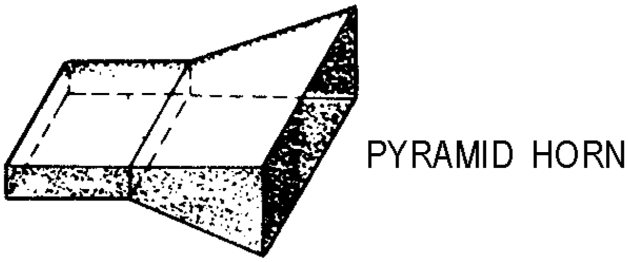


Figure 1-44C.—Waveguide horns. PYRAMID HORN.

As you may have noticed, horns are really simple antennas. They have several advantages over other impedance-matching devices, such as their large bandwidth and simple construction. The use of horns as antennas will be discussed further in chapter 3.

A waveguide may also be terminated in a resistive load that is matched to the characteristic impedance of the waveguide. The resistive load is most often called a DUMMY LOAD, because its only purpose is to absorb all the energy in a waveguide without causing standing waves.

There is no place on a waveguide to connect a fixed termination resistor; therefore, several special arrangements are used to terminate waveguides. One method is to fill the end of the waveguide with a graphite and sand mixture, as illustrated in figure 1-45A. When the fields enter the mixture, they induce a current flow in the mixture which dissipates the energy as heat. Another method figure 1-45B is to use a high-resistance rod placed at the center of the E field. The E field causes current to flow in the rod, and the high resistance of the rod dissipates the energy as a power loss, again in the form of heat.

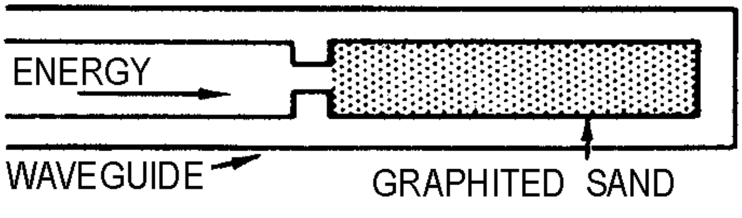


Figure 1-45A.—Terminating waveguides.

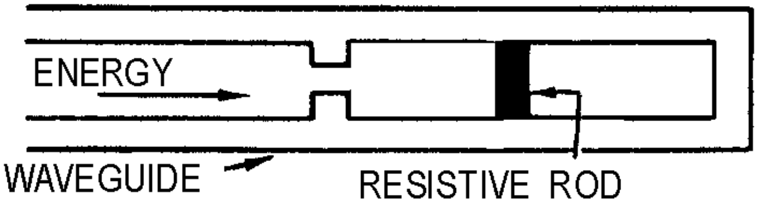


Figure 1-45B.—Terminating waveguides.

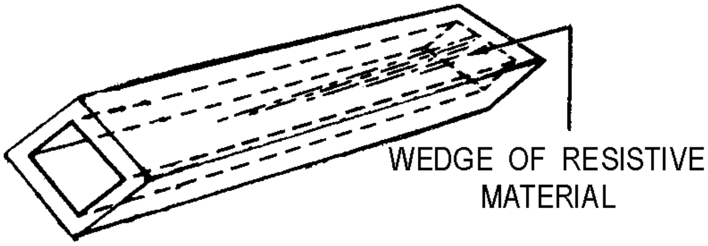


Figure 1-45C.—Terminating waveguides.

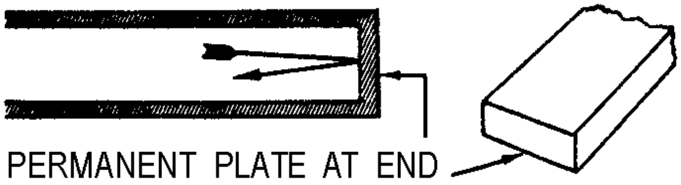


Figure 1-45D.—Terminating waveguides.

Still another method for terminating a waveguide is the use of a wedge of highly resistive material, as shown in of figure 1-45C. The plane of the wedge is placed perpendicular to the magnetic lines of force. When the H lines cut through the wedge, current flows in the wedge and causes a power loss. As with the other methods, this loss is in the form of heat. Since very little energy reaches the end of the waveguide, reflections are minimum.

All of the terminations discussed so far are designed to radiate or absorb the energy without reflections. In many instances, however, all of the energy must be reflected from the end of the waveguide. The best way to accomplish this is to permanently weld a metal plate at the end of the waveguide, as shown in figure 1-45D.

Q-37. What device is used to produce a gradual change in impedance at the end of a waveguide?

Q-38. When a waveguide is terminated in a resistive load, the load must be matched to what property of the waveguide?

Q-39. What is the primary purpose of a dummy load?

Q-40. The energy dissipated by a resistive load is most often in what form?

Waveguide Plumbing

Since waveguides are really only hollow metal pipes, the installation and the physical handling of waveguides have many similarities to ordinary plumbing. In light of this fact, the bending, twisting, joining, and installation of waveguides is commonly called waveguide plumbing. Naturally, waveguides are different in design from pipes that are designed to carry liquids or other substances. The design of a waveguide is determined by the frequency and power level of the electromagnetic energy it will carry. The following paragraphs explain the physical factors involved in the design of waveguides.

WAVEGUIDE BENDS.—The size, shape, and dielectric material of a waveguide must be constant throughout its length for energy to move from one end to the other without reflections. Any abrupt change in its size or shape can cause reflections and a loss in overall efficiency. When such a change is necessary, the bends, twists, and joints of the waveguides must meet certain conditions to prevent reflections.

Waveguides may be bent in several ways that do not cause reflections. One way is the gradual bend shown in figure 1-46. This gradual bend is known as an E bend because it distorts the E fields. The E bend must have a radius greater than two wavelengths to prevent reflections.

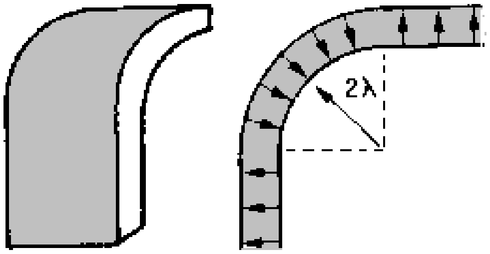


Figure 1-46.—Gradual E bend.

Another common bend is the gradual H bend (figure 1-47). It is called an H bend because the H fields are distorted when a waveguide is bent in this manner. Again, the radius of the bend must be greater than two wavelengths to prevent reflections. Neither the E bend in the "a" dimension nor the H bend in the "b" dimension changes the normal mode of operation.

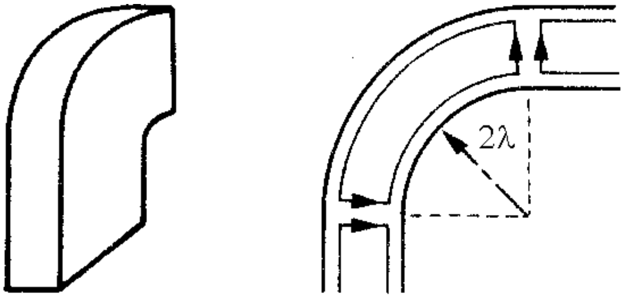


Figure 1-47.—Gradual H bend.

A sharp bend in either dimension may be used if it meets certain requirements. Notice the two 45-degree bends in figure 1-48; the bends are 1/4λ apart. The reflections that occur at the 45-degree bends cancel each other, leaving the fields as though no reflections have occurred.

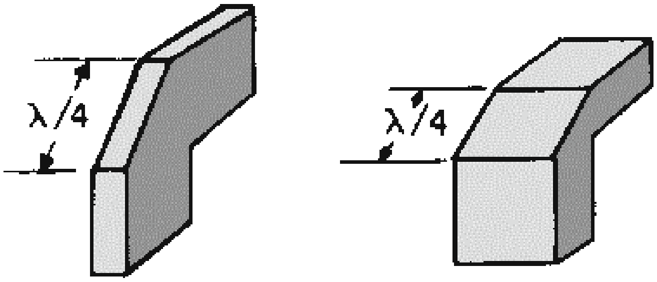


Figure 1-48.—Sharp bends.

Sometimes the electromagnetic fields must be rotated so that they are in the proper phase to match the phase of the load. This may be accomplished by twisting the waveguide as shown in figure 1-49. The twist must be gradual and greater than 2λ.

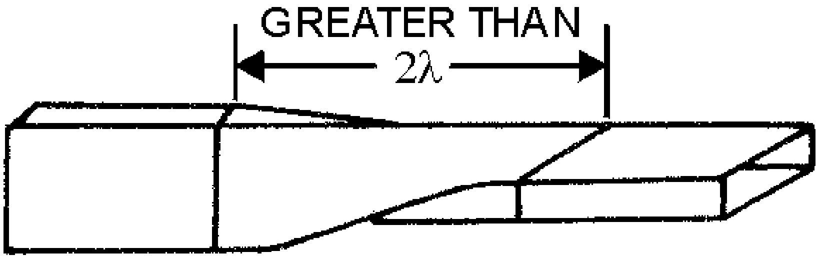


Figure 1-49.—Waveguide twist.

The flexible waveguide (figure 1-50) allows special bends which some equipment applications might require. It consists of a specially wound ribbon of conductive material, most commonly brass, with the inner surface plated with chromium. Power losses are greater in the flexible waveguide because the inner surfaces are not perfectly smooth. Therefore, it is only used in short sections where no other reasonable solution is available.

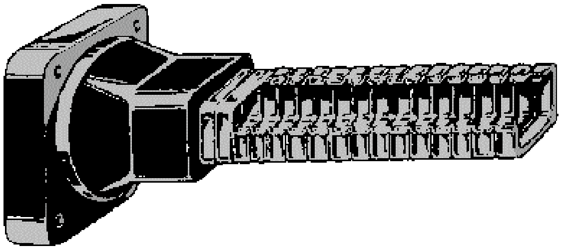


Figure 1-50.—Flexible waveguide.

WAVEGUIDE JOINTS.—Since an entire waveguide system cannot possibly be molded into one piece, the waveguide must be constructed in sections and the sections connected with joints. The three basic types of waveguide joints are the PERMANENT, the SEMIPERMANENT, and the ROTATING JOINTS. Since the permanent joint is a factory-welded joint that requires no maintenance, only the semipermanent and rotating joints will be discussed.

Sections of waveguide must be taken apart for maintenance and repair. A semipermanent joint, called a CHOKE JOINT, is most commonly used for this purpose. The choke joint provides good electromagnetic continuity between sections of waveguide with very little power loss.

A cross-sectional view of a choke joint is shown in figures 1-51A and 1-51B. The pressure gasket shown between the two metal surfaces forms an airtight seal. Notice in figure 1-51B that the slot is exactly 1/4λ from the "a" wall of the waveguide. The slot is also 1/4λ deep, as shown in figure 1-51A, and because it is shorted at point (1), a high impedance results at point (2). Point (3) is 1/4λ from point (2). The high impedance at point (2) results in a low impedance, or short, at point (3). This effect creates a good electrical connection between the two sections that permits energy to pass with very little reflection or loss.

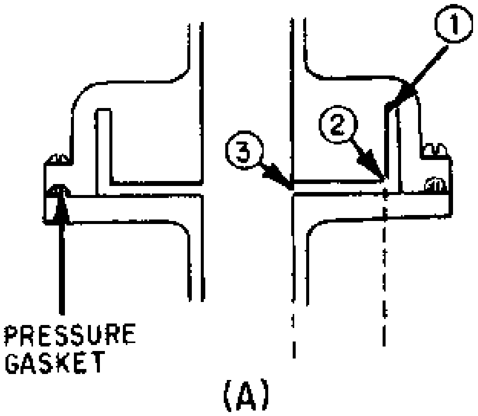


Figure 1-51A.—Choke joint.

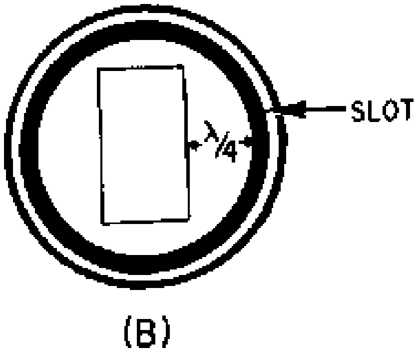


Figure 1-51B.—Choke joint.

Whenever a stationary rectangular waveguide is to be connected to a rotating antenna, a rotating joint must be used. A circular waveguide is normally used in a rotating joint. Rotating a rectangular waveguide would cause field pattern distortion. The rotating section of the joint, illustrated in figure 1-52, uses a choke joint to complete the electrical connection with the stationary section. The circular waveguide is designed so that it will operate in the $TM_{0,1}$ mode. The rectangular sections are attached as shown in the illustration to prevent the circular waveguide from operating in the wrong mode.

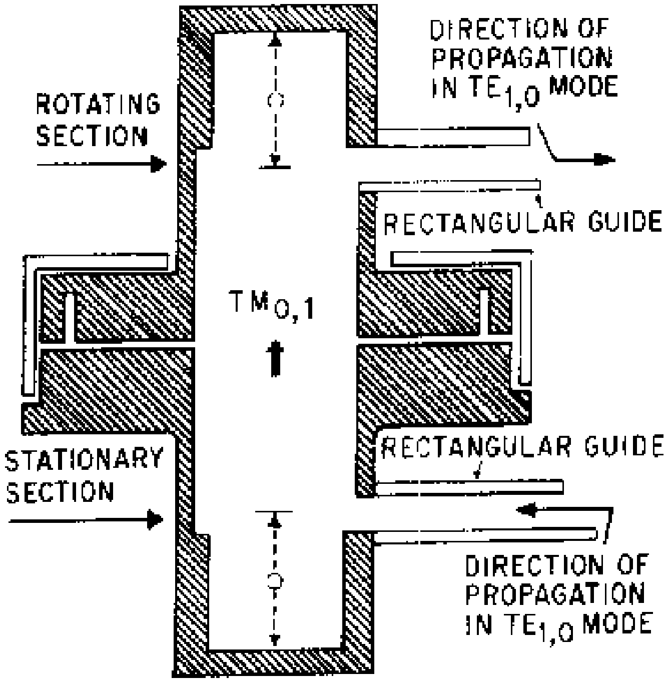


Figure 1-52.—Rotating joint.

Distance "O" is 3/4λ so that a high impedance will be presented to any unwanted modes. This is the most common design used for rotating joints, but other types may be used in specific applications.

WAVEGUIDE MAINTENANCE.—The installation of a waveguide system presents problems that are not normally encountered when dealing with other types of transmission lines. These problems often fall within the technician's area of responsibility. A brief discussion of waveguide handling, installation, and maintenance will help prepare you for this maintenance responsibility. Detailed information concerning waveguide maintenance in a particular system may be found in the technical manuals for the system.

Since a waveguide naturally has a low loss ratio, most losses in a waveguide system are caused by other factors. Improperly connected joints or damaged inner surfaces can decrease the efficiency of a system to the point that it will not work at all. Therefore, you must take great care when working with waveguides to prevent physical damage. Since waveguides are made from a soft, conductive material, such as copper or aluminum, they are very easy to dent or deform. Even the slightest damage to the inner surface of a waveguide will cause standing waves and, often, internal arcing. Internal arcing causes further damage to the waveguide in an action that is often self-sustaining until the waveguide is damaged beyond use. Part of your job as a technician will be to inspect the waveguide system for physical damage. The previously mentioned dents are only one type of physical damage that can decrease the efficiency of the system. Another problem occurs because waveguides are made from a conductive material such as copper while the structures of most ships are made from steel. When two dissimilar metals, such as copper and steel, are in direct contact, an electrical action called ELECTROLYSIS takes place that causes very rapid corrosion of the metals. Waveguides can be completely destroyed by electrolytic corrosion in a relatively short period of time if they are not isolated from direct contact with other metals. Any inspection of a waveguide system should include a detailed inspection of all support points to ensure that electrolytic corrosion is not taking place. Any waveguide that is exposed to the weather should be painted and all joints sealed. Proper painting prevents natural corrosion, and sealing the joints prevents moisture from entering the waveguide.

Moisture can be one of the worst enemies of a waveguide system. As previously discussed, the dielectric in waveguides is air, which is an excellent dielectric as long as it is free of moisture. Wet air, however, is a very poor dielectric and can cause serious internal arcing in a waveguide system. For this reason care is taken to ensure that waveguide systems are pressurized with air that is dry. Checking the pressure and moisture content of the waveguide air may be one of your daily system maintenance duties.

More detailed waveguide installation and maintenance information can be found in the technical manuals that apply to your particular system. Another good source is the *Electronics Installation and Maintenance Handbooks* (EIMB) published by Naval Sea Systems Command. *Installation Standards Handbook* EIMB, NAVSEA 0967-LP-000-0110, is the volume that deals with waveguide installation and maintenance.

Q-41. What is the result of an abrupt change in the size, shape, or dielectric of a waveguide?

Q-42. A waveguide bend must have what minimum radius?

Q-43. What is the most common type of waveguide joint?

Q-44. What is the most likely cause of losses in waveguide systems?

WAVEGUIDE DEVICES

The discussion of waveguides, up to this point, has been concerned only with the transfer of energy from one point to another. Many waveguide devices have been developed, however, that modify the energy in some fashion during transit. Some devices do nothing more than change the direction of the energy. Others have been designed to change the basic characteristics or power level of the electromagnetic energy.

This section will explain the basic operating principles of some of the more common waveguide devices, such as DIRECTIONAL COUPLERS, CAVITY RESONATORS, and HYBRID JUNCTIONS.

Directional Couplers

The directional coupler is a device that provides a method of sampling energy from within a waveguide for measurement or use in another circuit. Most couplers sample energy traveling in one direction only. However, directional couplers can be constructed that sample energy in both directions. These are called BIDIRECTIONAL couplers and are widely used in radar and communications systems.

Directional couplers may be constructed in many ways. The coupler illustrated in figure 1-53 is constructed from an enclosed waveguide section of the same dimensions as the waveguide in which the energy is to be sampled. The "b" wall of this enclosed section is mounted to the "b" wall of the waveguide from which the sample will be taken. There are two holes in the "b" wall between the sections of the coupler. These two holes are 1/4λ apart. The upper section of the directional coupler has a wedge of energy-absorbing material at one end and a pickup probe connected to an output jack at the other end. The absorbent material absorbs the energy not directed at the probe and a portion of the overall energy that enters the section.

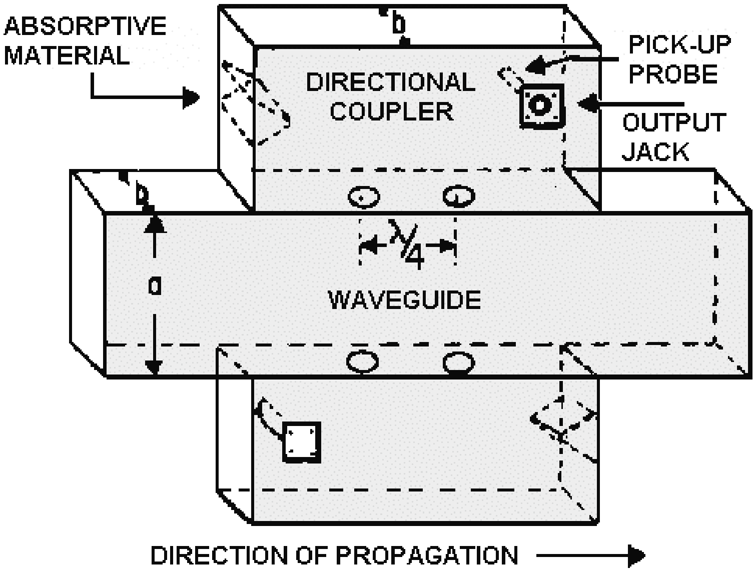


Figure 1-53.—Directional coupler.

Figure 1-54 illustrates two portions of the incident wavefront in a waveguide. The waves travel down the waveguide in the direction indicated and enter the coupler section through both holes. Since both portions of the wave travel the same distance, they are in phase when they arrive at the pickup probe. Because the waves are in phase, they add together and provide a sample of the energy traveling down the waveguide. The sample taken is only a small portion of the energy that is traveling down the waveguide. The magnitude of the sample, however, is proportional to the magnitude of the energy in the waveguide. The absorbent material is designed to ensure that the ratio between the sample energy and the energy in the waveguide is constant. Otherwise the sample would contain no useful information.

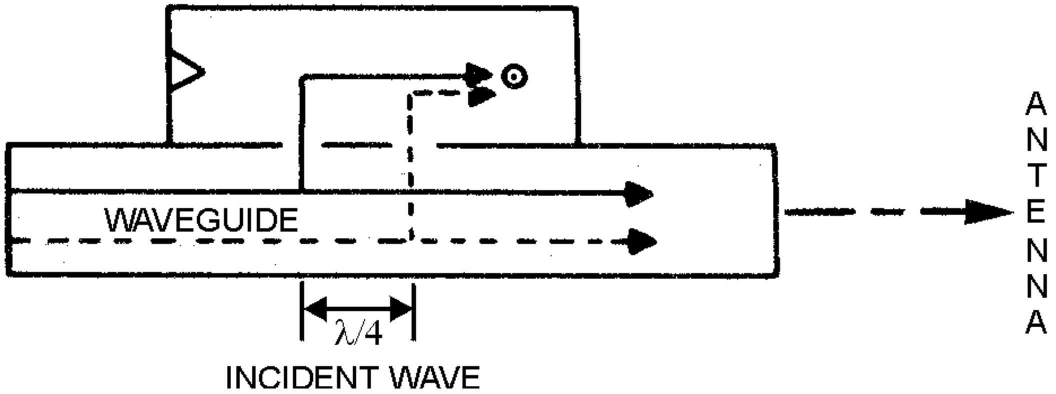


Figure 1-54.—Incident wave in a directional coupler designed to sample incident waves.

The ratio is usually stamped on the coupler in the form of an attenuation factor.

The effect of a directional coupler on any reflected energy is illustrated in figure 1-55. Note that these two waves do not travel the same distance to the pickup probe. The wave represented by the dotted line travels 1/2λ further and arrives at the probe 180 degrees out of phase with the wave represented by the solid line. Because the waves are 180 degrees out of phase at the probe, they cancel each other and no energy is induced in the pickup probe. When the reflected energy arrives at the absorbent material, it adds and is absorbed by the material.

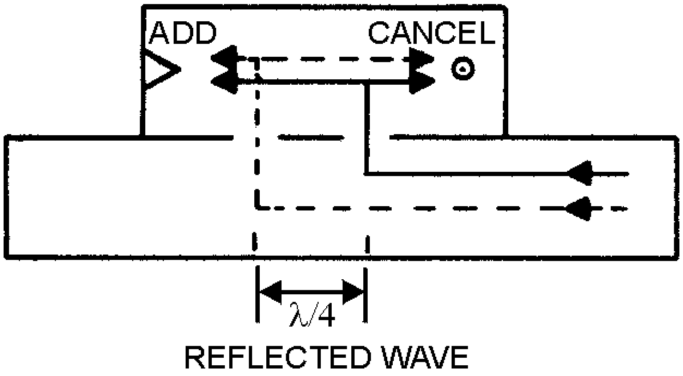


Figure 1-55.—Reflected wave in a directional coupler.

A directional coupler designed to sample reflected energy is shown in figure 1-56. The absorbent material and the probe are in opposite positions from the directional coupler designed to sample the incident energy. This positioning causes the two portions of the reflected energy to arrive at the probe in phase, providing a sample of the reflected energy. The sampled transmitted energy, however, is absorbed by the absorbent material.

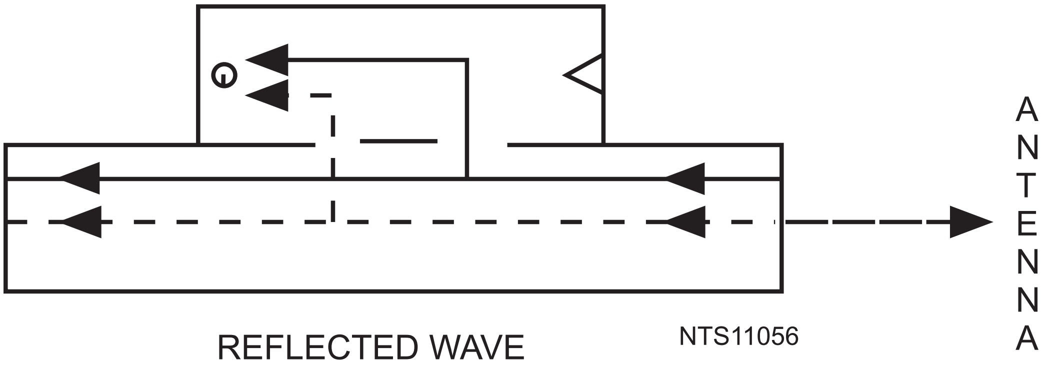


Figure 1-56.—Directional coupler designed to sample reflected energy.

A simple bidirectional coupler for sampling both transmitted and reflected energy can be constructed by mounting two directional couplers on opposite sides of a waveguide, as shown in figure 1-57.

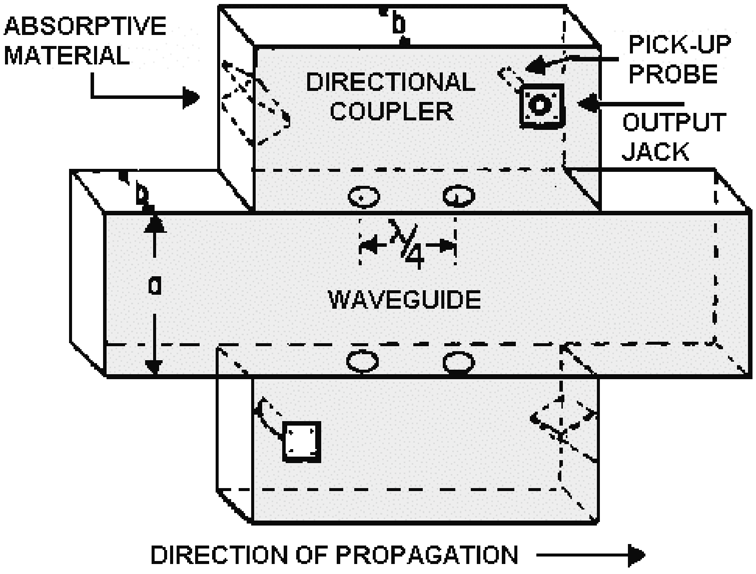


Figure 1-57.—Bidirectional coupler.

Q-45. What is the primary purpose of a directional coupler?

Q-46. How far apart are the two holes in a simple directional coupler?

Q-47. What is the purpose of the absorbent material in a directional coupler?

Q-48. In a directional coupler that is designed to sample the incident energy, what happens to the two portions of the wavefront when they arrive at the pickup probe?

Q-49. What happens to reflected energy that enters a directional coupler that is designed to sample incident energy?

Cavity Resonators

In ordinary electronic equipment a resonant circuit consists of a coil and a capacitor that are connected either in series or in parallel. The resonant frequency of the circuit is increased by reducing the capacitance, the inductance, or both. A point is eventually reached where the inductance and the capacitance can be reduced no further. This is the highest frequency at which a conventional circuit can oscillate.

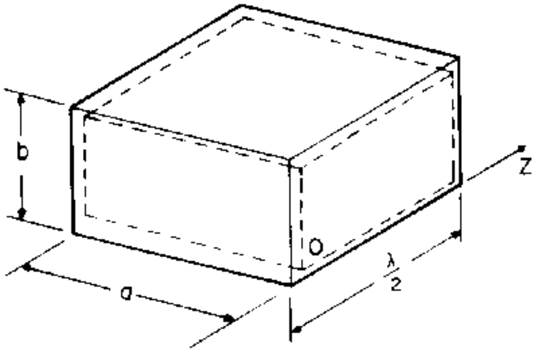
The upper limit for a conventional resonant circuit is between 2000 and 3000 megahertz. At these frequencies, the inductance may consist of a coil of one-half turn, and the capacitance may simply be the stray capacitance of the coil. Tuning a one-half turn coil is very difficult and tuning stray capacitance is even more difficult. In addition, such a circuit will handle only very small amounts of current.

NEETS, Module 10, *Introduction to Wave Propagation* explained that a 1/4λ section of transmission line can act as a resonant circuit. The same is true of a 1/4λ section of waveguide. Since a waveguide is hollow, it can also be considered as a RESONANT CAVITY.

By definition, a resonant cavity is any space completely enclosed by conducting walls that can contain oscillating electromagnetic fields and possess resonant properties. The cavity has many advantages and uses at microwave frequencies. Resonant cavities have a very high Q and can be built to handle relatively large amounts of power. Cavities with a Q value in excess of 30,000 are not uncommon. The high Q gives these devices a narrow bandpass and allows very accurate tuning. Simple, rugged construction is an additional advantage.

Although cavity resonators, built for different frequency ranges and applications, have a variety of shapes, the basic principles of operation are the same for all.

One example of a cavity resonator is the rectangular box shown in figure 1-58A. It may be thought of as a section of rectangular waveguide closed at both ends by conducting plates. The frequency at which the resonant mode occurs is 1/2λ of the distance between the end plates. The magnetic and electric field patterns in the rectangular cavity are shown in figure 1-58B.



(A) RESONATOR SHAPE

Figure 1-58A.—Rectangular waveguide cavity resonator. RESONATOR SHAPE.

MAGNETIC FIELD PATTERN

ELECTRIC FIELD PATTERN

(B) FIELD PATTERNS OF A SIMPLE MODE.

Figure 1-58B.—Rectangular waveguide cavity resonator. FIELD PATTERNS OF A SIMPLE MODE.

The rectangular cavity is only one of many cavity devices that are useful as high-frequency resonators. Figures 1-59A, 1-59B, 1-59C, and 1-59D show the development of a cylindrical resonant cavity from an infinite number of quarter-wave sections of transmission line. In figure 1-59A the 1/4λ section is shown to be equivalent to a resonant circuit with a very small amount of inductance and capacitance. Three 1/4λ sections are joined in parallel in figure 1-59B. Note that although the current-carrying ability of several 1/4λ sections is greater than that of any one section, the resonant frequency is unchanged. This occurs because the addition of inductance in parallel lowers the total inductance, but the addition of capacitance in parallel increases the total capacitance by the same proportion. Thus, the resonant frequency remains the same as it was for one section. The increase in the number of current paths also decreases the total resistance and increases the Q of the resonant circuit. Figure 1-59C shows an intermediate step in the development of the cavity. Figure 1-59D shows a completed cylindrical resonant cavity with a diameter of 1/2λ at the resonant frequency.

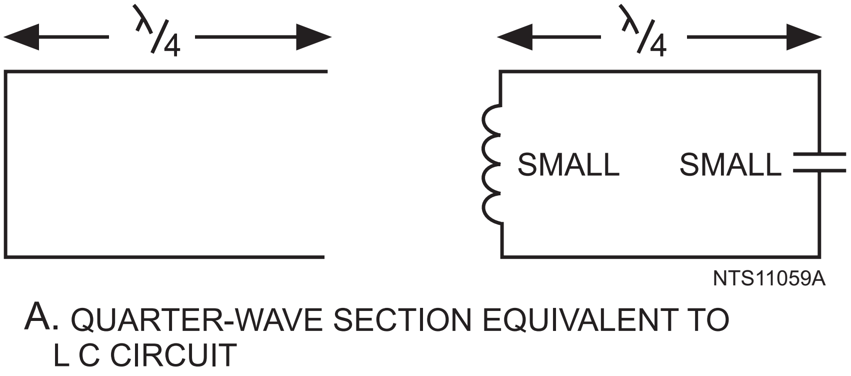


Figure 1-59A.—Development of a cylindrical resonant cavity. QUARTER-WAVE SECTION EQUIVALENT TO LC CIRCUIT.

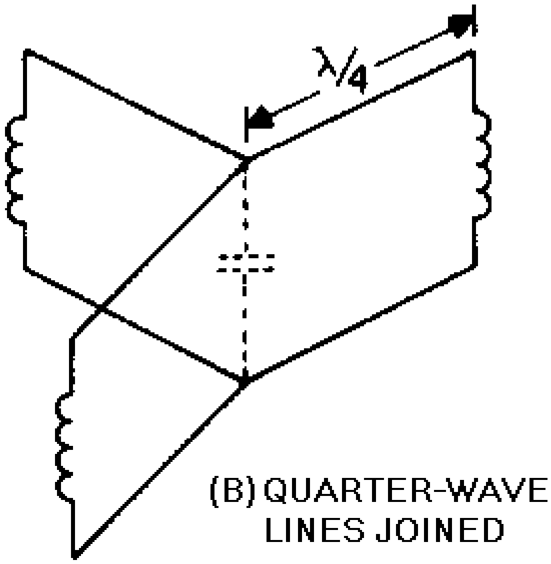


Figure 1-59B.—Development of a cylindrical resonant cavity. QUARTER-WAVE LINES JOINED.

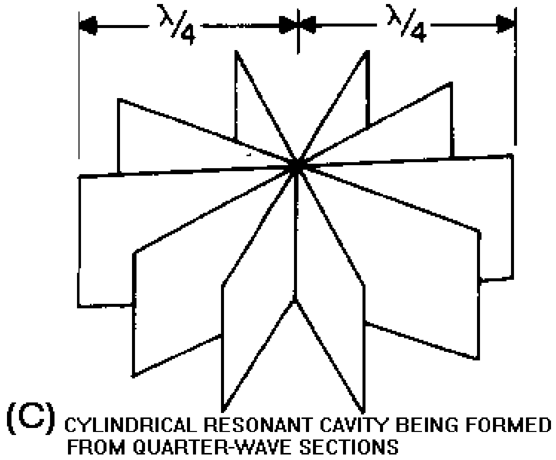


Figure 1-59C.—Development of a cylindrical resonant cavity. CYLINDRICAL RESONANT CAVITY BEING FORMED FROM QUARTER-WAVE SECTIONS.

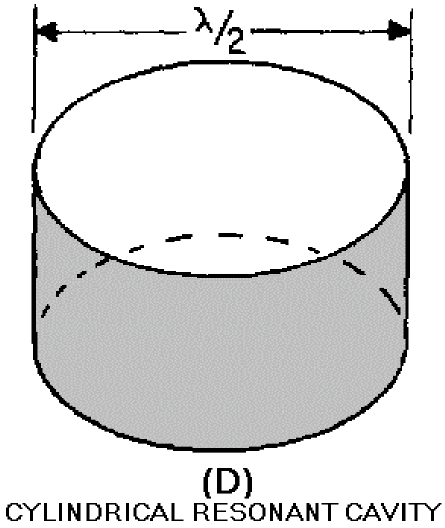


Figure 1-59D.—Development of a cylindrical resonant cavity. CYLINDRICAL RESONANT CAVITY.

There are two variables that determine the primary frequency of any resonant cavity. The first variable is PHYSICAL SIZE. In general, the smaller the cavity, the higher its resonant frequency. The second controlling factor is the SHAPE of the cavity. Figure 1-60 illustrates several cavity shapes that are commonly used. Remember from the previously stated definition of a resonant cavity that any completely enclosed conductive surface, regardless of its shape, can act as a cavity resonator.

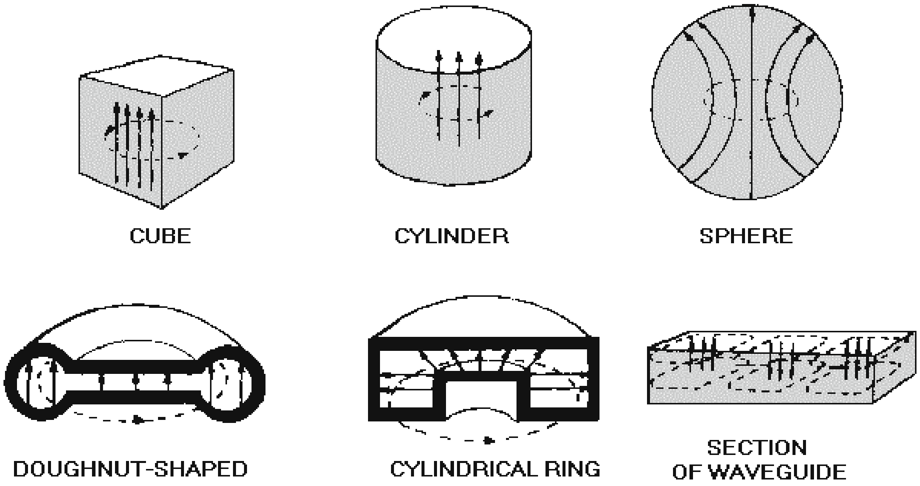

CUBE
CYLINDER
SPHERE
DOUGHNUT-SHAPED
CYLINDRICAL RING
SECTION OF WAVEGUIDE

Figure 1-60.—Several types of cavities.

Cavity resonators are energized in basically the same manner as waveguides and have a similar field distribution. If the cavity shown in figure 1-61 were energized in the TE mode, the electromagnetic wave would reflect back and forth along the Z axis and form standing waves. These standing waves would form a field configuration within the cavity that would have to satisfy the same boundary conditions as those in a waveguide. Modes of operation in the cavity are described in terms of the fields that exist in the X, Y, and Z dimensions. Three subscripts are used; the first subscript indicates the number of $1/2\lambda$ along the X axis; the second subscript indicates the number of $1/2\lambda$ along the Y axis; and the third subscript indicates the number of $1/2\lambda$ along the Z axis.

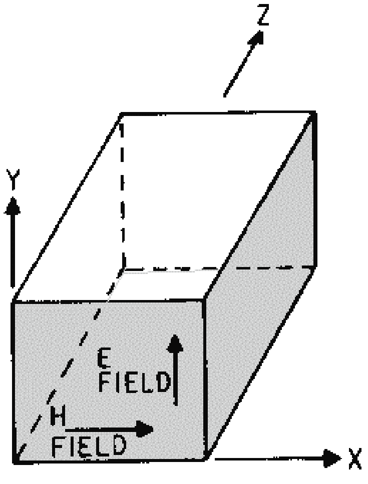


Figure 1-61.—Rectangular cavity resonator.

Energy can be inserted or removed from a cavity by the same methods that are used to couple energy into and out of waveguides. The operating principles of probes, loops, and slots are the same whether used in a cavity or a waveguide. Therefore, any of the three methods can be used with cavities to inject or remove energy.

The resonant frequency of a cavity can be varied by changing any of three parameters: cavity volume, cavity capacitance, or cavity inductance. Changing the frequencies of a cavity is known as TUNING. The mechanical methods of tuning a cavity may vary with the application, but all methods use the same electrical principles.

A mechanical method of tuning a cavity by changing the volume (VOLUME TUNING) is illustrated in figure 1-62. Varying the distance d will result in a new resonant frequency because the inductance and the capacitance of the cavity are changed by different amounts. If the volume is decreased, the resonant frequency will be higher. The resonant frequency will be lower if the volume of the cavity is made larger.

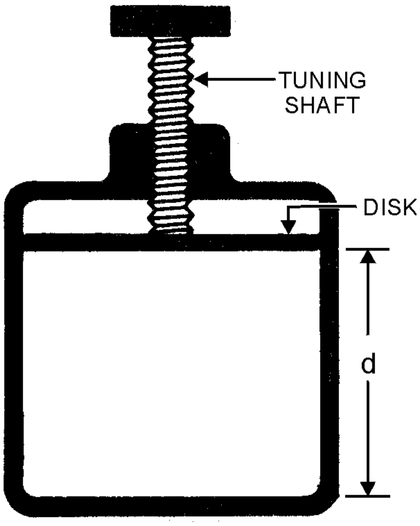
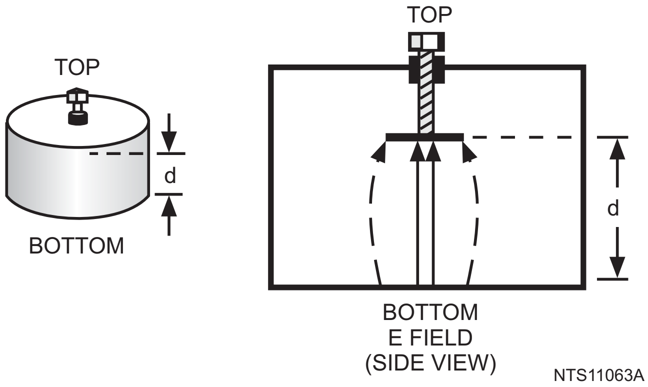


Figure 1-62.—Cavity tuning by volume.

CAPACITIVE TUNING of a cavity is shown in figure 1-63A. An adjustable slug or screw is placed in the area of maximum E lines. The distance d represents the distance between two capacitor plates. As the slug is moved in, the distance between the two plates becomes smaller and the capacitance increases. The increase in capacitance causes a decrease in the resonant frequency. As the slug is moved out, the resonant frequency of the cavity increases.



A. CHANGING THE CAPACITANCE

Figure 1-63A.—Methods of changing the resonant frequency of a cavity. CHANGING THE CAPACITANCE.

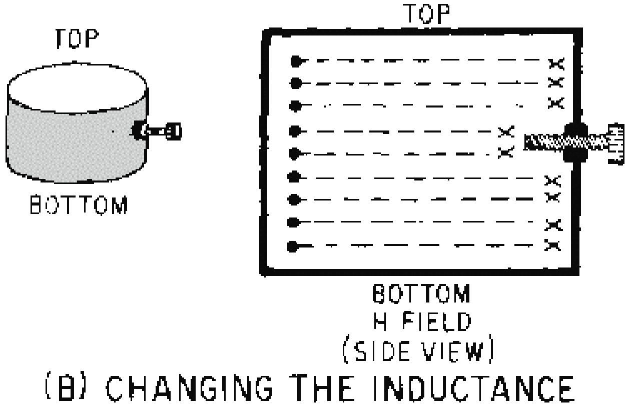


Figure 1-63B.—Methods of changing the resonant frequency of a cavity. CHANGING THE INDUCTANCE.

INDUCTIVE TUNING is accomplished by placing a nonmagnetic slug in the area of maximum H lines, as shown in figure 1-63B. The changing H lines induce a current in the slug that sets up an opposing H field. The opposing field reduces the total H field in the cavity, and therefore reduces the total inductance. Reducing the inductance, by moving the slug in, raises the resonant frequency. Increasing the inductance, by moving the slug out, lowers the resonant frequency.

Resonant cavities are widely used in the microwave range, and many of the applications will be studied in chapter 2. For example, most microwave tubes and transmitting devices use cavities in some form to generate microwave energy. Cavities are also used to determine the frequency of the energy traveling in a waveguide, since conventional measurement devices do not work well at microwave frequencies.

Q-50. What two variables determine the primary frequency of a resonant cavity?

Q-51. Energy can be inserted or removed from a cavity by what three methods?

Q-52. Inductive tuning of a resonant cavity is accomplished by placing a nonmagnetic slug in what area?

Waveguide Junctions

You may have assumed that when energy traveling down a waveguide reaches a junction, it simply divides and follows the junction. This is not strictly true. Different types of junctions affect the energy in different ways. Since waveguide junctions are used extensively in most systems, you need to understand the basic operating principles of those most commonly used.

The T JUNCTION is the most simple of the commonly used waveguide junctions. T junctions are divided into two basic types, the E-TYPE and the H-TYPE. HYBRID JUNCTIONS are more complicated developments of the basic T junctions. The MAGIC-T and the HYBRID RING are the two most commonly used hybrid junctions.

E-TYPE T JUNCTION.—An E-type T junction is illustrated in figure 1-64, view (A). It is called an E-type T junction because the junction arm extends from the main waveguide in the same direction as the E field in the waveguide.

Figure 1-64, view (B), illustrates cross-sectional views of the E-type T junction with inputs fed into the various arms. For simplicity, the magnetic lines that are always present with an electric field have been omitted. In view (K), the input is fed into arm b and the outputs are taken from the a and c arms. When the E field arrives between points 1 and 2, point 1 becomes positive and point 2 becomes negative. The positive charge at point 1 then induces a negative charge on the wall at point 3. The negative charge at point 2 induces a positive charge at point 4. These charges cause the fields to form 180 degrees out of phase in the main waveguide; therefore, the outputs will be 180 degrees out of phase with each other. In view (L), two in-phase inputs of equal amplitude are fed into the a and c arms. The signals at points 1 and 2 have the same phase and amplitude. No difference of potential exists across the entrance to the b arm, and no energy will be coupled out. However, when the two signals fed into the a and c arms are 180 degrees out of phase, as shown in view (M), points 1 and 2 have a difference of potential. This difference of potential induces an E field from point 1 to point 2 in the b arm, and energy is coupled out of this arm. Views (N) and (P) illustrate two methods of obtaining two outputs with only one input.

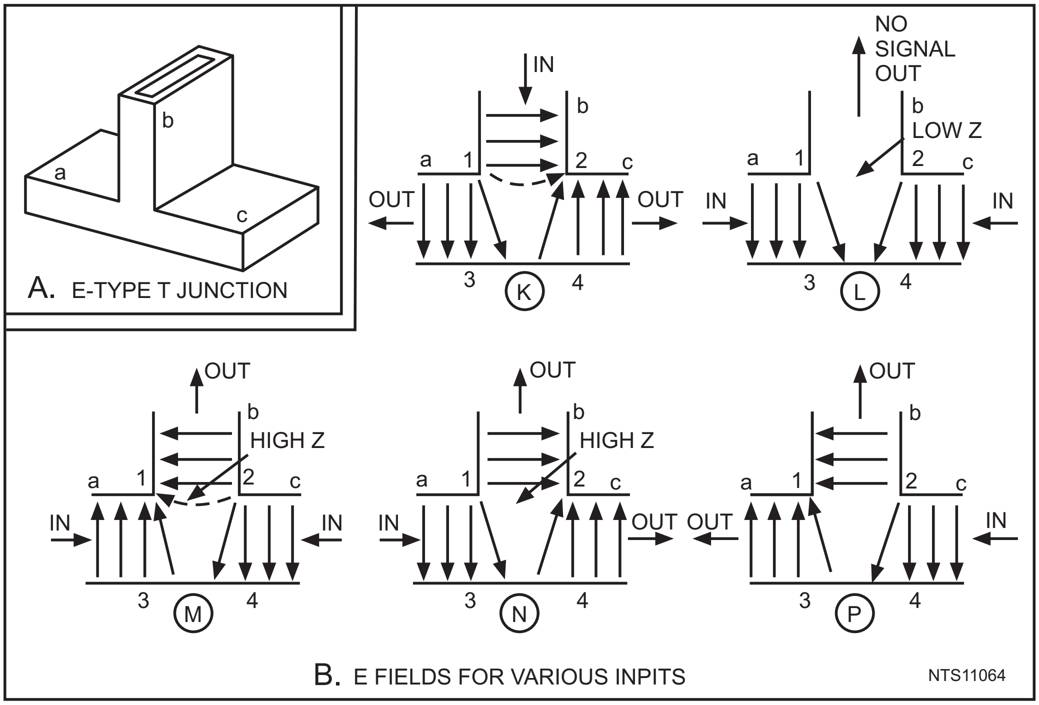


Figure 1-64.—E fields in an E-type T junction.

H-TYPE T JUNCTION.—An H-type T junction is illustrated in figure 1-65A. It is called an H-type T junction because the long axis of the "b" arm is parallel to the plane of the magnetic lines of force in the waveguide. Again, for simplicity, only the E lines are shown in this figure. Each X indicates an E line moving away from the observer. Each dot indicates an E line is moving toward the observer.

In view (1) of figure 1-65B, the signal is fed into arm b and in-phase outputs are obtained from the a and c arms. In view (2), in-phase signals are fed into arms a and c and the output signal is obtained from the b arm because the fields add at the junction and induce E lines into the b arm. If 180-degree-out-of-phase signals are fed into arms a and c, as shown in view (3), no output is obtained from the b arm because the opposing fields cancel at the junction. If a signal is fed into the a arm, as shown in view (4), outputs will be obtained from the b and c arms. The reverse is also true. If a signal is fed into the c arm, outputs will be obtained from the a and b arms.

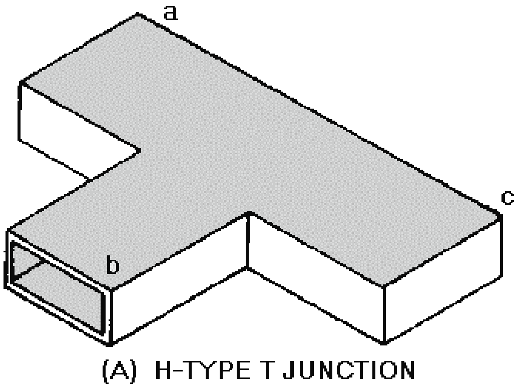


Figure 1-65A.—E fields in an H-type junction. H-TYPE T JUNCTION.

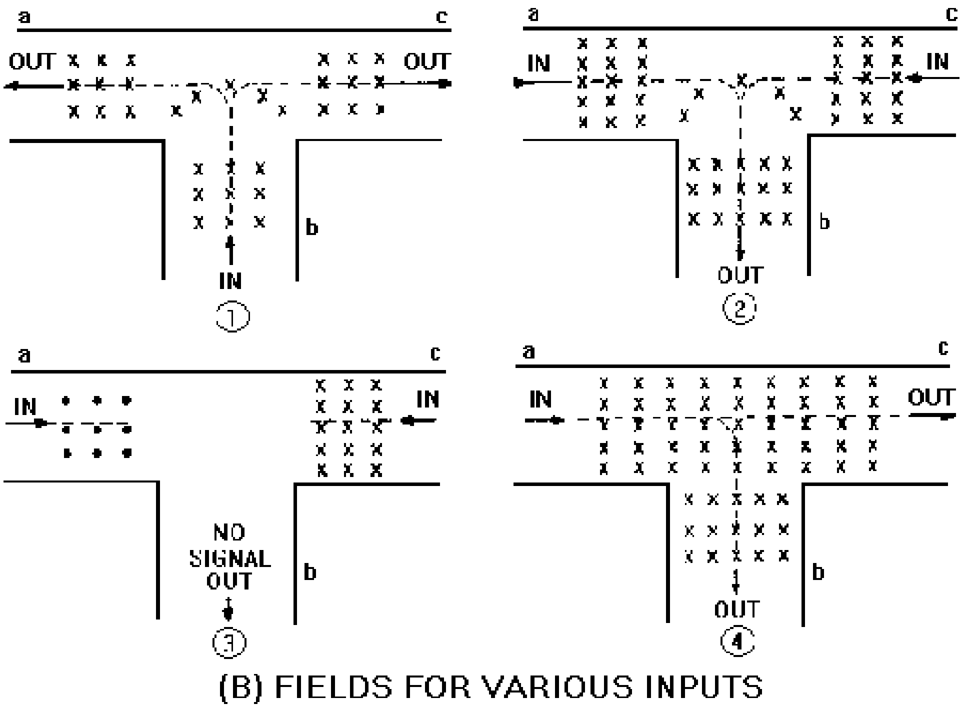


Figure 1-65B.—E fields in an H-type junction. FIELDS FOR VARIOUS INPUTS.

MAGIC-T HYBRID JUNCTION.—A simplified version of the magic-T hybrid junction is shown in figure 1-66. The magic-T is a combination of the H-type and E-type T junctions. The most common application of this type of junction is as the mixer section for microwave radar receivers. Its operation as a mixer will be discussed in later *NEETS* modules. At present, only the fields within the magic-T junction will be discussed.

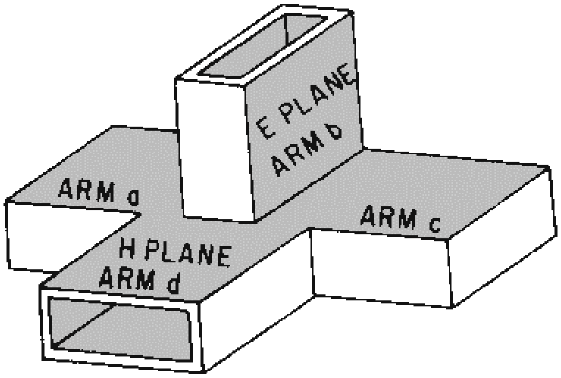


Figure 1-66.—Magic-T hybrid junction.

If a signal is fed into the b arm of the magic- T, it will divide into two out-of-phase components. As shown in figure 1-67A, these two components will move into the a and c arms. The signal entering the b arm will not enter the d arm because of the zero potential existing at the entrance of the d arm. The potential must be zero at this point to satisfy the boundary conditions of the b arm. This absence of potential is illustrated in figures 1-67B and 1-67C where the magnitude of the E field in the b arm is indicated by the length of the arrows. Since the E lines are at maximum in the center of the b arm and minimum at the edge where the d arm entrance is located, no potential difference exists across the mouth of the d arm.

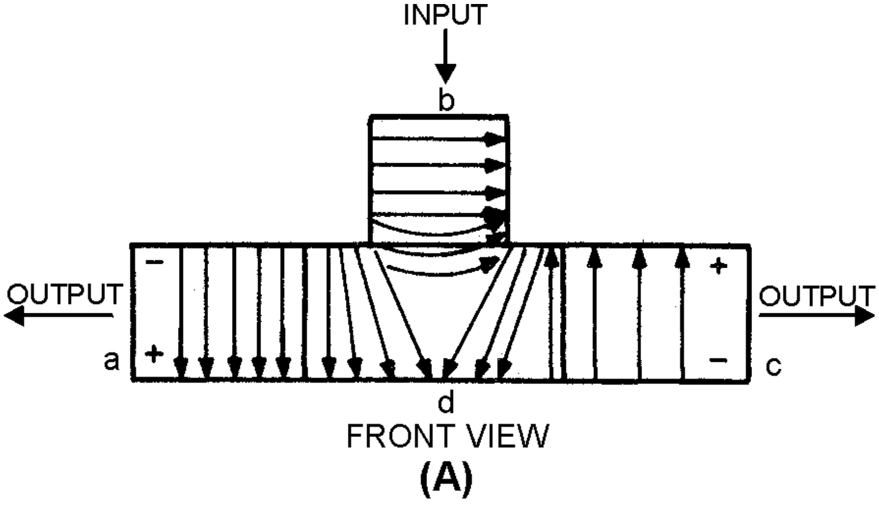


Figure 1-67A.—Magic-T with input to arm b.

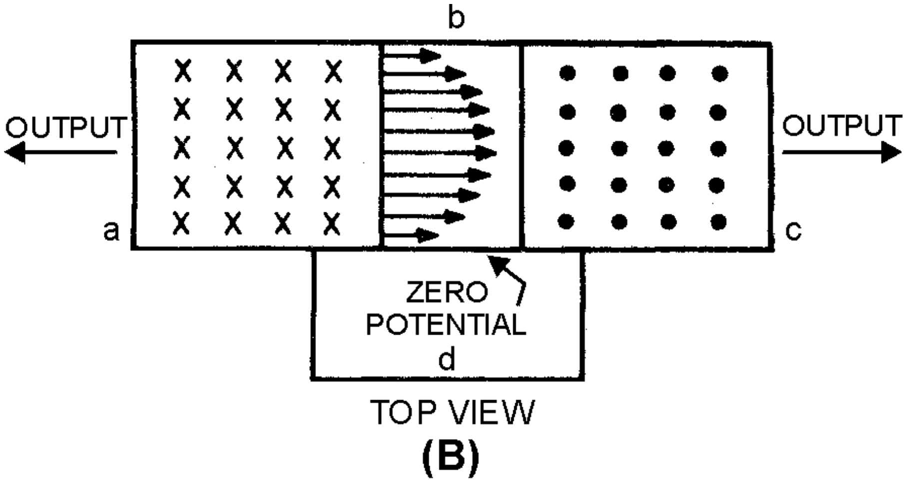


Figure 1-67B.—Magic-T with input to arm b.

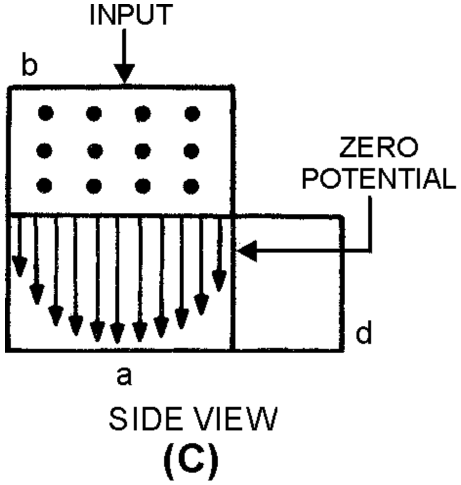


Figure 1-67C.—Magic-T with input to arm b.

In summary, when an input is applied to arm b of the magic-T hybrid junction, the output signals from arms a and c are 180 degrees out of phase with each other, and no output occurs at the d arm.

The action that occurs when a signal is fed into the d arm of the magic-T is illustrated in figure 1-68. As with the H-type T junction, the signal entering the d arm divides and moves down the a and c arms as outputs which are in phase with each other and with the input. The shape of the E fields in motion is shown by the numbered curved slices. As the E field moves down the d arm, points 2 and 3 are at an equal potential. The energy divides equally into arms a and c, and the E fields in both arms become identical in shape. Since the potentials on both sides of the b arm are equal, no potential difference exists at the entrance to the b arm, resulting in no output.

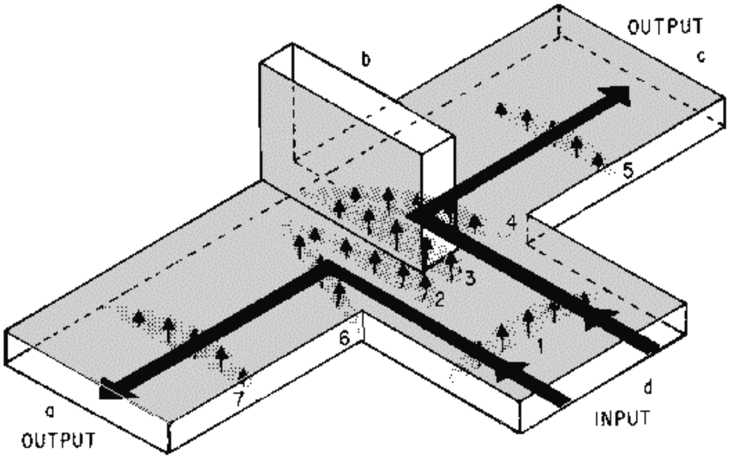


Figure 1-68.—Magic-T with input to arm d.

When an input signal is fed into the a arm as shown in figure 1-69, a portion of the energy is coupled into the b arm as it would be in an E-type T junction. An equal portion of the signal is coupled through the d arm because of the action of the H-type junction. The c arm has two fields across it that are out of phase with each other. Therefore the fields cancel, resulting in no output at the c arm. The reverse of this action takes place if a signal is fed into the c arm, resulting in outputs at the b and d arms and no output at the a arm.

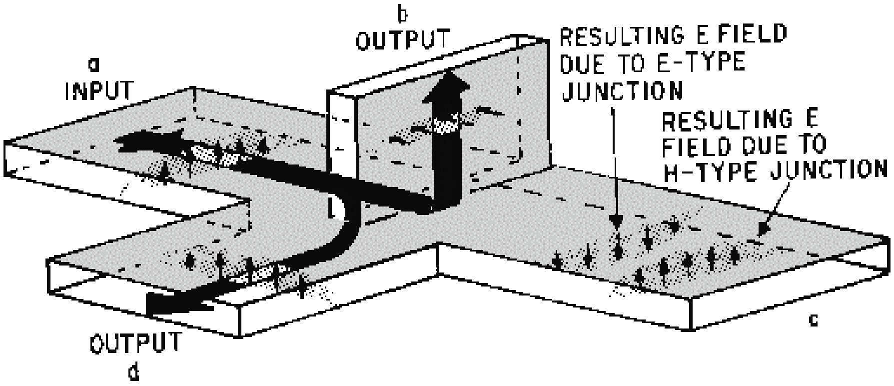


Figure 1-69.—Magic-T with input to arm a.

Unfortunately, when a signal is applied to any arm of a magic-T, the flow of energy in the output arms is affected by reflections. Reflections are caused by impedance mismatching at the junctions. These reflections are the cause of the two major disadvantages of' the magic-T. First, the reflections represent a power loss since all the energy fed into the junction does not reach the load which the arms feed. Second, the reflections produce standing waves that can result in internal arching. Thus the maximum power a magic-T can handle is greatly reduced.

Reflections can be reduced by using some means of' impedance matching that does not destroy the shape of' the junctions. One method is shown in figure 1-70. A post is used to match the H plane, and an iris is used to match the E plane. Even though this method reduces reflections, it lowers the power-handling capability even further.

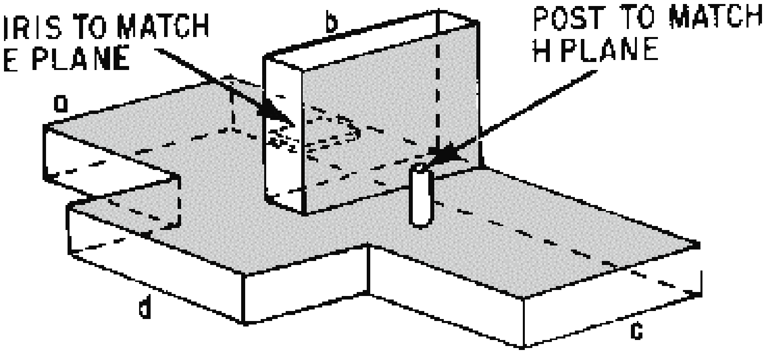


Figure 1-70.—Magic-T impedance matching.

HYBRID RING.—A type of hybrid junction that overcomes the power limitation of the magic-T is the hybrid ring, also called a RAT RACE. The hybrid ring, illustrated in figure 1-71A, is actually a modification of the magic-T. It is constructed of rectangular waveguides molded into a circular pattern. The arms are joined to the circular waveguide to form E-type T junctions. Figure 1-71B shows, in wavelengths, the dimensions required for a hybrid ring to operate properly.

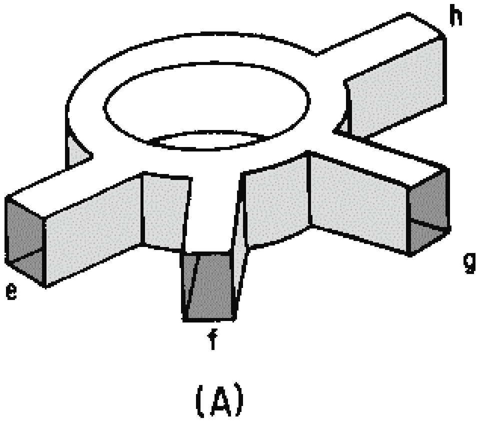


Figure 1-71A.—Hybrid ring with wavelength measurements.

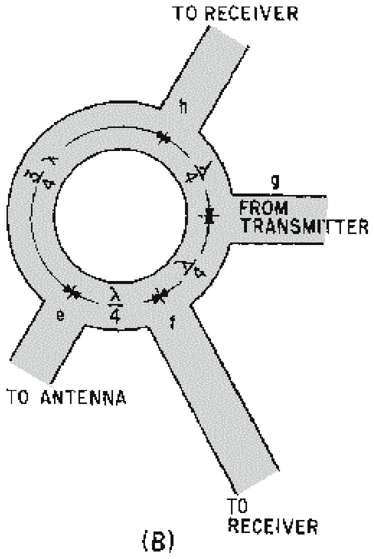


Figure 1-71B.—Hybrid ring with wavelength measurements.

The hybrid ring is used primarily in high-powered radar and communications systems to perform two functions. During the transmit period, the hybrid ring couples microwave energy from the transmitter to the antenna and allows no energy to reach the receiver. During the receive cycle, the hybrid ring couples energy from the antenna to the receiver and allows no energy to reach the transmitter. Any device that performs both of these functions is called a DUPLEXER. A duplexer permits a system to use the same antenna for both transmitting and receiving. Since the only common application of the hybrid ring is as a duplexer, the details of hybrid ring operation will be explained in later *NEETS* modules concerning duplexers.

Q-53. What are the two basic types of T junctions?

Q-54. Why is the H-type T junction so named?

Q-55. The magic-T is composed of what two basic types of T junctions?

Q-56. What are the primary disadvantages of the magic-T?

Q-57. What type of junctions are formed where the arms of a hybrid ring meet the main ring?

Q-58. Hybrid rings are used primarily for what purpose?

Ferrite Devices

A FERRITE is a device that is composed of material that causes it to have useful magnetic properties and, at the same time, high resistance to current flow. The primary material used in the construction of ferrites is normally a compound of iron oxide with impurities of other oxides added. The compound of iron oxide retains the properties of the ferromagnetic atoms, and the impurities of the other oxides increase the resistance to current flow. This combination of properties is not found in conventional magnetic materials. Iron, for example, has good magnetic properties but a relatively low resistance to current flow. The low resistance causes eddy currents and significant power losses at high frequencies (You may want to review *NEETS*, Module 2, *Introduction to Alternating Current and Transformers*, Chapter 5). Ferrites, on the other hand, have sufficient resistance to be classified as semiconductors.

The compounds used in the composition of ferrites can be compared to the more familiar compounds used in transistors. As in the construction of transistors, a wide range of magnetic and electrical properties can be produced by the proper choice of atoms in the right proportions. An example of a ferrite device is shown in figure 1-72.

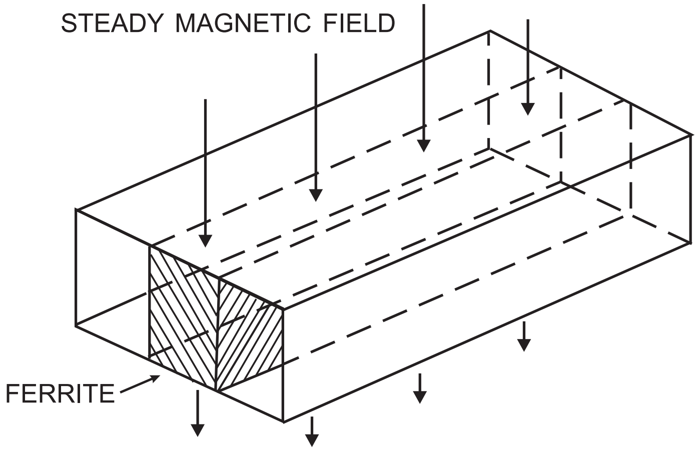


Figure 1-72.—Ferrite attenuator.

Ferrites have long been used at conventional frequencies in computers, television, and magnetic recording systems. The use of ferrites at microwave frequencies is a relatively new development and has had considerable influence on the design of microwave systems. In the past, the microwave equipment was made to conform to the frequency of the system and the design possibilities were limited. The unique properties of ferrites provide a variable reactance by which microwave energy can be manipulated to conform to the microwave system. At present, ferrites are used as LOAD ISOLATORS, PHASE SHIFTERS, VARIABLE ATTENUATORS, MODULATORS, and SWITCHES in microwave systems. The operation of ferrites as isolators, attenuators, and phase shifters will be explained in the following paragraphs. The operation of ferrites in other applications will be explained in later *NEETS* modules. Ferromagnetism is a continuation of the conventional domain theory of magnetism that was explained in *NEETS*, Module 1, *Matter, Energy, and Direct Current*. A review of the section on magnetism might be helpful to you at this point.

The magnetic property of any material is a result of electron movement within the atoms of the material. Electrons have two basic types of motion. The most familiar is the ORBITAL movement of the electron about the nucleus of the atom. Less familiar, but even more important, is the movement of the electron about its own axis, called ELECTRON SPIN.

You will recall that magnetic fields are generated by current flow. Since current is the movement of electrons, the movement of the electrons within an atom create magnetic fields. The magnetic fields caused by the movement of the electrons about the nucleus have little effect on the magnetic properties of a material. The magnetic fields caused by electron spin combine to give a material magnetic properties. The different types of electron movement are illustrated in figure 1-73. In most materials the spin axes of the electrons are so randomly arranged that the magnetic fields largely cancel out and the material displays no significant magnetic properties. The electron spin axes within some materials, such as iron and nickel, can be caused to align by applying an external magnetic field. The alignment of the electrons within a material causes the magnetic fields to add, and the material then has magnetic properties.

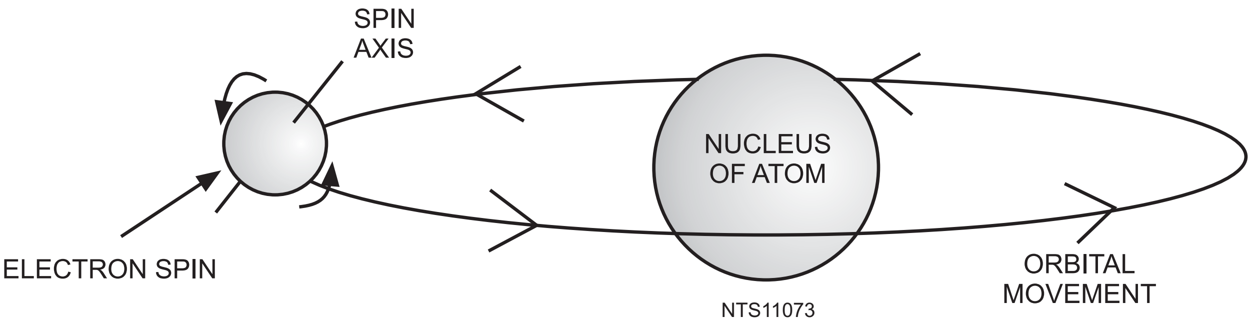


Figure 1-73.—Two types of electron movement.

In the absence of an external force, the axis of any spinning object tends to remain pointed in one direction. Spinning electrons behave the same way. Therefore, once the electrons are aligned, they tend to remain aligned even when the external field is removed. Electron alignment in a ferrite is caused by the orbital motion of the electrons about the nucleus and the force that holds the atom together. When a static magnetic field is applied, the electrons try to align their spin axes with the new force. The attempt of the electrons to balance between the interaction of the new force and the binding force causes the electrons to wobble on their axes, as shown in figure 1-74. The wobble of the electrons has a natural resonant WOBBLE FREQUENCY that varies with the strength of the applied field. Ferrite action is based on this behavior of the electrons under the influence of an external field and the resulting wobble frequency.

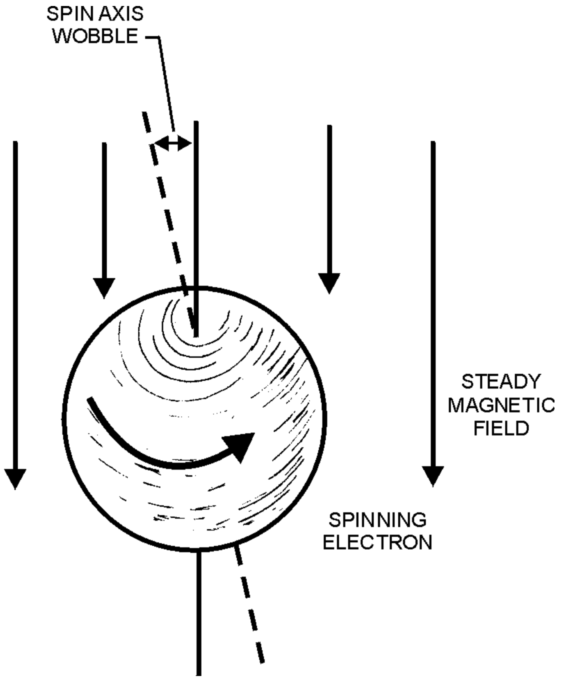


Figure 1-74.—Electron wobble in a magnetic field.

FERRITE ATTENUATORS.—A ferrite attenuator can be constructed that will attenuate a particular microwave frequency and allow all others to pass unaffected. This can be done by placing a ferrite in the center of a waveguide, as shown in figure 1-72. The ferrite must be positioned so that the magnetic fields caused by its electrons are perpendicular to the energy in the waveguide. A steady external field causes the electrons to wobble at the same frequency as the energy that is to be attenuated.

Since the wobble frequency is the same as the energy frequency, the energy in the waveguide always adds to the wobble of the electrons. The spin axis of the electron changes direction during the wobble motion and energy is used. The force causing the increase in wobble is the energy in the waveguide. Thus, the energy in the waveguide is attenuated by the ferrite and is given off as heat. Energy in the waveguide that is a different frequency from the wobble frequency of the ferrite is largely unaffected because it does not increase the amount of electron wobble. The resonant frequency of electron wobble can be varied over a limited range by changing the strength of the applied magnetic field.

FERRITE ISOLATORS.—An isolator is a ferrite device that can be constructed so that it allows microwave energy to pass in one direction but blocks energy in the other direction in a waveguide. This isolator is constructed by placing a piece of ferrite off-center in a waveguide, as shown in figure 1-75. A magnetic field is applied by the magnet and adjusted to make the electron wobble frequency of the ferrite equal to the frequency of the energy traveling down the waveguide. Energy traveling down the waveguide from left to right will set up a rotating magnetic field that rotates through the ferrite material in the same direction as the natural wobble of the electrons. The aiding magnetic field increases the wobble of the ferrite electrons so much that almost all of the energy in the waveguide is absorbed and dissipated as heat. The magnetic fields caused by energy traveling from right to left rotate in the opposite direction through the ferrite and have very little effect on the amount of electron wobble. In this case the fields attempt to push the electrons in the direction opposite the natural wobble and no large movements occur. Since no overall energy exchange takes place, energy traveling from right to left is affected very little.

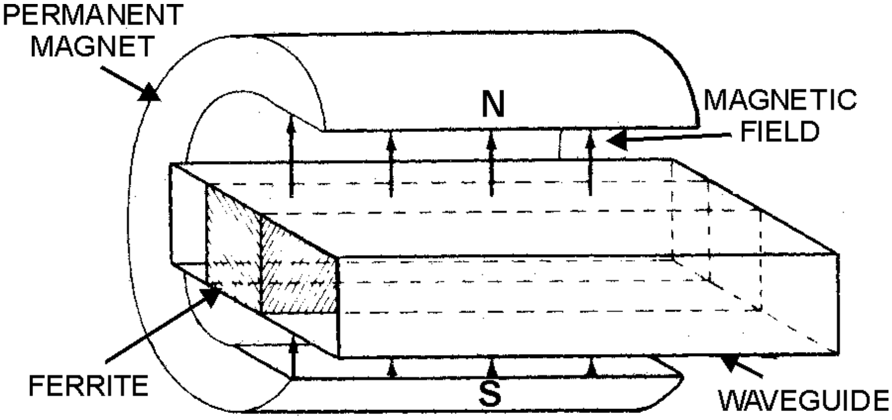


Figure 1-75.—One-way isolator.

FERRITE PHASE SHIFTER.—When microwave energy is passed through a piece of ferrite in a magnetic field, another effect occurs. If the frequency of the microwave energy is much greater than the electron wobble frequency, the plane of polarization of the wavefront is rotated. This is known as the FARADAY ROTATION EFFECT and is illustrated in figure 1-76. A ferrite rod is placed along the axis of the waveguide, and a magnetic field is set up along the axis by a coil. As a wavefront enters the section containing the ferrite, it sets up a limited motion in the electrons. The magnetic fields of the wavefront and the wobbling electrons interact, and the polarization of the wavefront is rotated. The amount of rotation depends upon the length of the ferrite rod. The direction of rotation depends upon the direction of the external magnetic field and can be reversed by reversing the field. The direction of rotation will remain constant, no matter what direction the energy in the waveguide travels, as long as the external field is not changed.

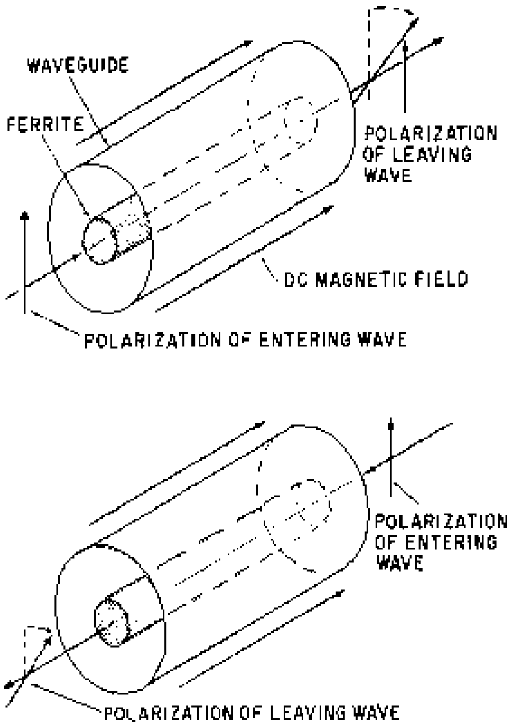


Figure 1-76.—Faraday rotation.

Q-59. Ferrite devices are useful in microwave applications because they possess what properties?

Q-60. Which of the two types of electron motion (orbital movement and electron spin) is more important in the explanation of magnetism?

Q-61. The interaction between an external field and the binding force of an atom causes electrons to do what?

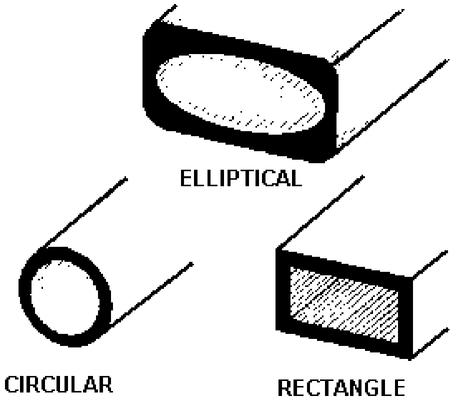
Q-62. The resonant frequency of electron wobble can be changed by variation of what force?

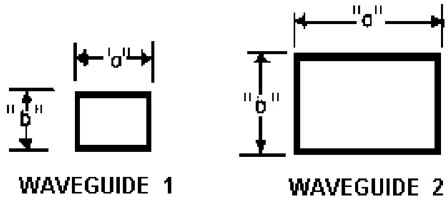
Q-63. Rotating the plane of polarization of a wavefront by passing it through a ferrite device is called what?

SUMMARY

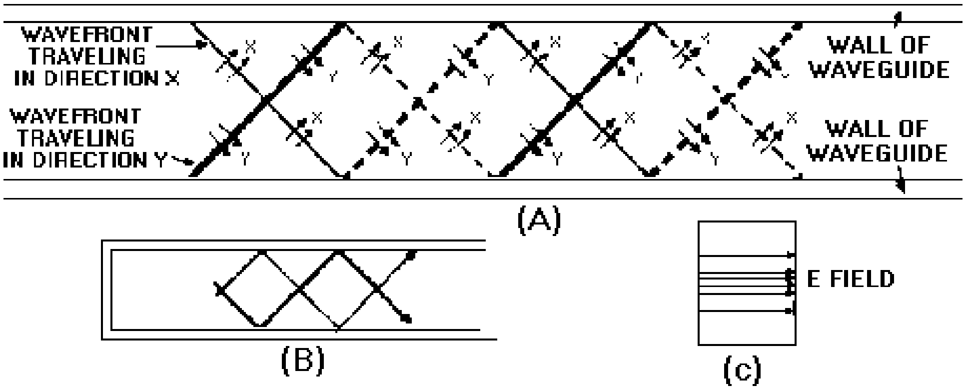
This chapter has presented information on waveguide theory and application. The information that follows summarizes the important points of this chapter.

WAVEGUIDES are the primary methods of transporting microwave energy. Waveguides have fewer losses and greater power-handling capability than transmission lines. The physical size of the waveguides becomes too great for use at frequencies less than 1000 megahertz. Waveguides are made in three basic shapes, as shown in the first illustration. The wide, or "a," dimension determines the frequency range of the waveguide, and the narrow, or "b," dimension determines power-handling capability as shown in the second illustration. Waveguides handle a small range of frequencies both above and below the primary operating frequency. Energy is transported through waveguides by the interaction of electric and magnetic fields, abbreviated E FIELD and H FIELD, respectively. The density of the E field varies at the same rate as the applied voltage. If energy is to travel through a waveguide, two BOUNDARY CONDITIONS must be met: (1) An electric field, to exist at the surface of a conductor, must be perpendicular to the conductor, and (2) a varying magnetic field must exist in closed loops parallel to the conductors and perpendicular to the electric field.

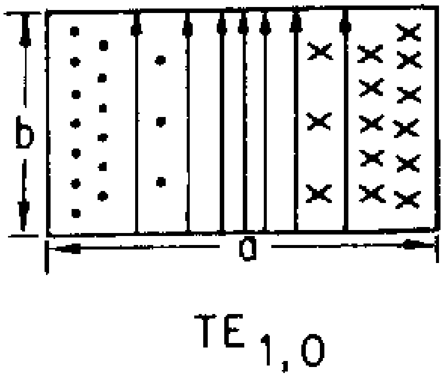




WAVEFRONTS travel down a waveguide by reflecting from the side walls in a zigzag pattern, as shown in the figure. The striking angle, or angle of incidence (θ), is the same as the angle of reflection (θ), causing the reflected wavefront to have the same shape as the incident wavefront. The velocity of wavefronts traveling down a waveguide is called the GROUP VELOCITY because of the zigzag path of these wavefronts. The group velocity is slower than the velocity of wavefronts through space.

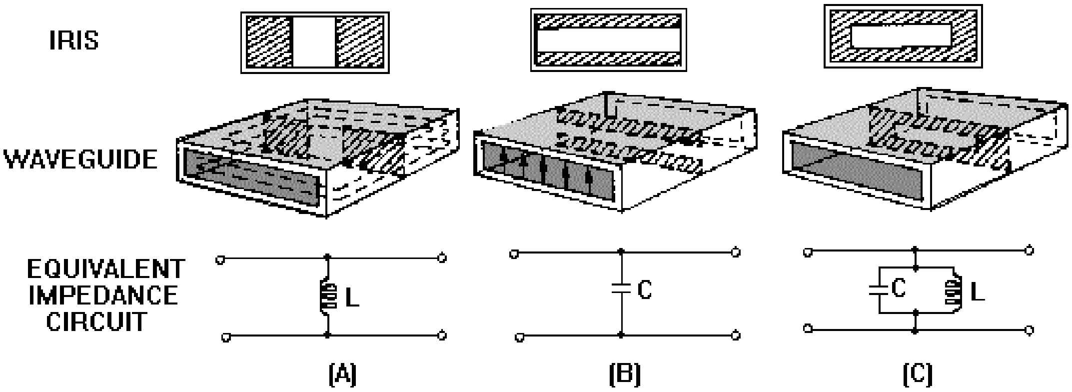


The **MODES** in waveguides are divided into two categories: (1) the TRANSVERSE ELECTRIC (TE) mode and (2) the TRANSVERSE MAGNETIC (TM) mode. Subscripts are used to complete the description of the various TE and TM modes. The dominant mode for rectangular waveguides is shown in the figure.



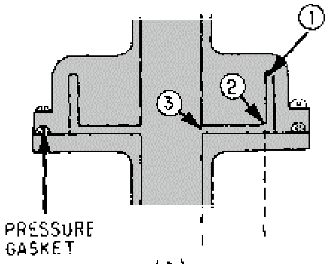
WAVEGUIDE INPUT/OUTPUT METHODS are divided into three basic categories: PROBES, LOOPS, and SLOTS. Size, shape, and placement in the waveguide are critical factors in the efficiency of all three input/output methods.

WAVEGUIDE/IMPEDANCE MATCHING is often necessary to reduce reflections caused by a MISMATCH between the waveguide and the load. Matching devices called IRISES, shown in the illustration, are used to introduce either capacitance or inductance (or a combination of both) into a waveguide. Conductive POSTS and SCREWS can also be used for impedance matching in waveguides.

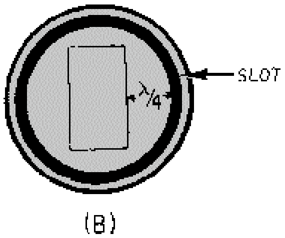


WAVEGUIDE TERMINATIONS prevent standing waves at the end of a waveguide system. They are usually specially constructed HORNS or absorptive loads called DUMMY LOADS.

WAVEGUIDE PLUMBING refers to the bends, twists, and joints necessary to install waveguides. E bends, H bends, and twists must have a radius greater than two wavelengths. The CHOKE JOINT, shown in the figure, is most often used to connect two pieces of waveguide. The ROTATING JOINT is used when a waveguide must be connected to a rotating load such as an antenna.

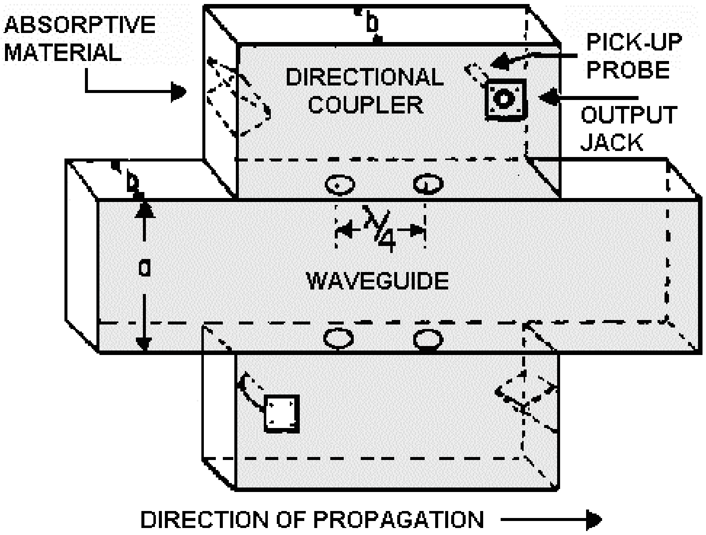


(A)

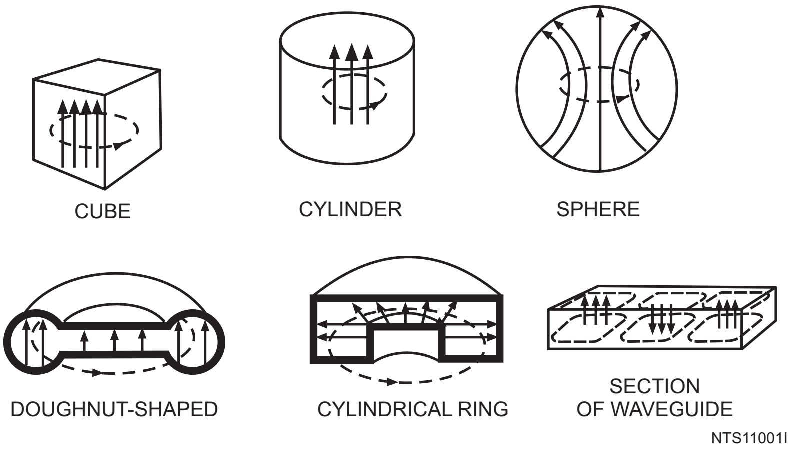


(B)

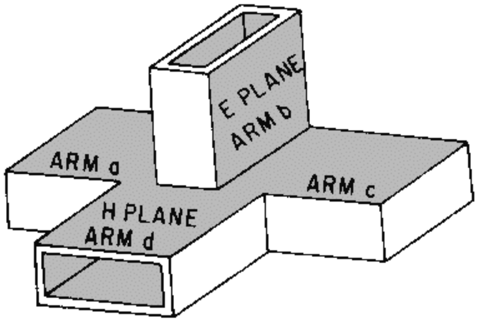
DIRECTIONAL COUPLERS are devices that permit the sampling of the energy in a waveguide. Directional couplers may be constructed to sample energy in one direction only or in both directions. The energy removed by the directional coupler is a small sample that is proportional to the magnitude of the energy in the waveguide. An example of a directional coupler is shown in the illustration.



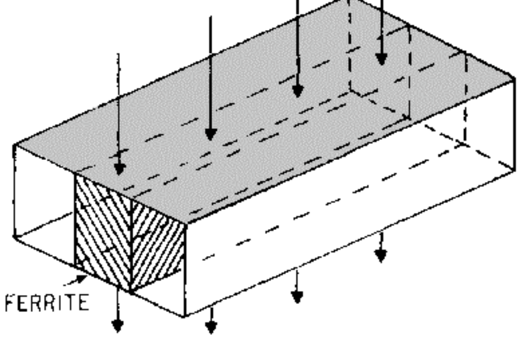
A **RESONANT CAVITY** is any space completely enclosed by conductive walls that can contain oscillating electromagnetic fields and can possess resonant properties. Several cavity shapes are shown in the illustration.



WAVEGUIDE JUNCTIONS are of several basic types. The T-JUNCTION may be either of the E-TYPE or the H-TYPE. The effect on the input energy depends upon which arm is used as the input. The MAGIC-T HYBRID JUNCTION, shown at the right, is a combination of the E- and H-type T junctions.



FERRITE DEVICES combine magnetic properties with a high resistance to current flow. Ferrites are constructed from compounds of ferrous metal oxides to achieve the desired characteristics. The fact that the spin axes of electrons will wobble at a natural resonant frequency when subjected to an external magnetic field is the basic principle of operation of ferrite devices. The position of a typical ferrite device within a waveguide is shown in the figure.



ANSWERS TO QUESTIONS Q1. THROUGH Q63.

A-1. Microwave region.

A-2. Electromagnetic field theory.

A-3. The electromagnetic fields are completely confined.

A-4. Conductive material.

A-5. Copper loss.

A-6. Skin effect.

A-7. Air.

A-8. Physical size.

A-9. The characteristics of the dielectric of a capacitor.

A-10. A shorted quarter-wave section called a metallic insulator.

A-11. The "a" dimension.

A-12. The bus bar becomes wider.

A-13. Energy will no longer pass through the waveguide.

A-14. The interaction of the electric and magnetic fields.

A-15. The relative strength of the field.

A-16. Magnetic lines of force must form a continuous closed loop.

A-17. The H lines cancel.

A-18. The field must be perpendicular to the conductors.

A-19. Decrease to zero.

A-20. The angles are equal.

A-21. Cutoff frequency.

A-22. Slower.

A-23. Group velocity.

A-24. Mode of operation.

A-25. Dominant mode.

A-26. 1.71 times the diameter.

A-27. Transverse electric (TE) and transverse magnetic (TM).

A-28. TE.

A-29. Second.

A-30. First.

A-31. Size and shape.

A-32. Slots and apertures.

A-33. Standing waves that cause power losses, a reduction in power-handling capability, and an increase in frequency and sensitivity.

A-34. Metal plates.

A-35. Inductive.

A-36. As a shunt resistance.

A-37. Horn.

A-38. Characteristic impedance.

A-39. Absorb all energy without producing standing waves.

A-40. Heat.

A-41. Reflections.

A-42. Greater than 2 wavelengths.

A-43. Choke joint.

A-44. Improperly connected joints or damaged inner surface.

A-45. Sampling energy within a waveguide.

A-46. 1/4 wavelength.

A-47. Absorb the energy not directed at the pick-up probe and a portion of the overall energy.

A-48. The wavefront portions add.

A-49. The reflected energy adds at the absorbent material and is absorbed.

A-50. Size and shape of the cavity.

A-51. Probes, loops, and slots.

A-52. The area of maximum H lines.

A-53. E-type and H-type.

A-54. The junction arm extends in a direction parallel to the H lines in the main waveguide.

A-55. E-type and H-type.

A-56. Low power-handling capability and power losses.

A-57. Basic E-type junctions.

A-58. High-power duplexes.

A-59. Magnetic properties and high resistance.

A-60. Electron spin.

A-61. Wobble at a natural resonant frequency.

A-62. The applied magnetic field.

A-63. Faraday rotation.