9

Antennas

The preceding chapter dealt at length with the various methods of propagation of radio waves, while only briefly mentioning how they might be transmitted or received. The word *antenna* was mentioned on a number of occasions! It is no secret that, in order to couple to space the output of a transmitter or the input of a receiver, some sort of interface is essential. A structure must be provided that is capable of radiating electromagnetic waves or receiving them.

This chapter acquaints the student with antenna fundamentals and continues with a consideration of simple wire radiators in free space. Several important antenna characteristics are defined and discussed. Among them are *antenna gain, resistance, bandwidth,* and *beamwidth*. Just as the ground has a significant effect on the propagation of waves, so it modifies the properties of antennas—hence the effects of ground are discussed in detail. Then, antenna coupling and HF antenna arrays are discussed. The final two major topics are microwave antennas, which are generally the most spectacular, and wideband antennas, which are generally the most complex in appearance. These last two subjects occupy more than one-third of the chapter and include antennas with *parabolic reflectors, horn antennas, lenses, helical antennas,* and *log-periodic arrays*.

OBJECTIVES

Upon completing the material in Chapter 9, the student will be able to:

Explain the evolution of the basic dipole antenna.

Define the term *elementary doublet (Hertzian dipole)*.

Compute the field strength of the doublet.

Determine current and voltage distributions.

Calculate the physical and/or electrical length of an antenna system.

Understand the terms *antenna gain, effective radiated power, field intensity radiation, resistance bandwidth, beamwidth,* and *polarization*.

Recognize the effect of ground on the antenna and antenna height.

Compare the optimum length of an antenna with its effective length.

Understand antenna coupling and its importance to the system.

Recognize the characteristics of various high-frequency antenna systems.

9-1 BASIC CONSIDERATIONS

The study of antennas must include a quick review of impedance matching (basic transformer theory) and resonant circuits. It was pointed out that maximum power transfer could be achieved only when the source matched the load. The antenna must have the ability to match the transmission line (source impedance 70 Ω, coax 300-Ω twin lead) and the load (the atmosphere, 377 Ω). At radio frequencies, and depending on physical length, a wire can be an impedance-matching device.

The antenna also must act somewhat as a resonant circuit; i.e., it must have the ability to transfer energy alternately from electrostatic to electromagnetic. If the Z match is correct, the energy being transferred will radiate energy into the atmosphere in the same way a transformer transforms energy from primary to secondary. This discussion is an oversimplification of the process encountered in RF transmission but can serve as a visual basis for further discussion (see Figure 9-1).

An antenna is a structure that is generally a metallic object, often a wire or group of wires, used to convert high-frequency current into electromagnetic waves, and vice versa. Apart from their different functions, transmitting and receiving antennas have similar characteristics, which means that their behavior is reciprocal.

The spacing, length, and shape of the device are related to the wavelength λ of the desired transmitter frequency; i.e., mechanical length is inversely proportional to the numerical value of the frequency.

$$T = 1/f \tag{9-1}$$

where T = time

f = frequency

1 MHz = 1.0 μs = 300 m

2 MHz = 0.5 μs = 150 m

Therefore, for an antenna operating at 50 MHz, $t = 1/f = 0.02\ \mu\text{s} = 6$ m, and wavelength = 300 m × time $\mu\text{s} = c/f = 3 \times 10^8/f$.

9-1.1 Electromagnetic Radiation

When RF energy is fed into a mismatched transmission line, standing waves occur. See Chapter 8 for more details. Energy is lost or radiated into the space surrounding the line. This process is considered unwanted in the transfer of energy to the radiation

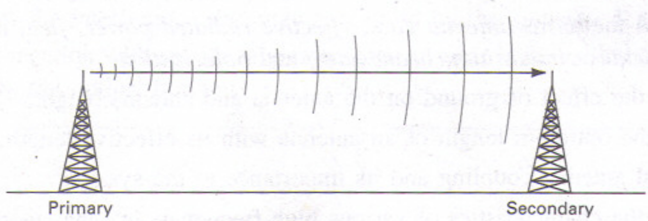

FIGURE 9-1 Transmitter-receiver energy transfer system.

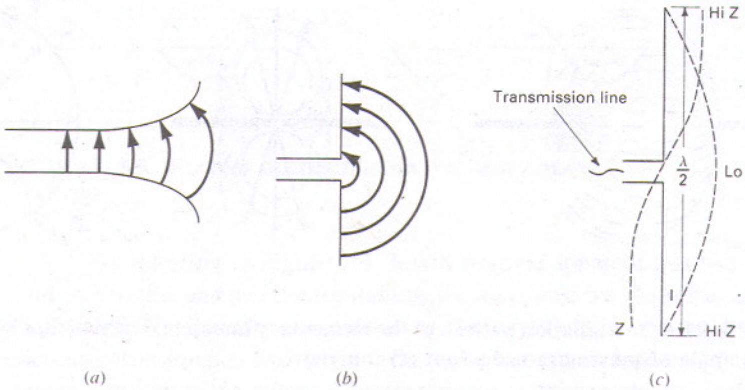

FIGURE 9-2 Evolution of the dipole. (*a*) Opened-out transmission line; (*b*) conductors in line; (*c*) half-wave dipole (center-fed).

device. If we examine this process and expand upon it (Figure 9-2*a*), we can see, by separating the ends of the transmission line, that more surface area of the wire is exposed to the atmosphere and enhances the radiation process.

The radiation efficiency of this system is improved even more when the two wires are bent at 90° (right angles) to each other (Figure 9-2*b*). The electric and magnetic fields are now fully coupled to the surrounding space instead of being confined between the two wires, and maximum radiation results. *This type of radiator is called a dipole*. When the total length of the two wires is a half wavelength, the antenna is called a half-wave dipole.

This configuration has similar characteristics to its equivalent length transmission line (¼ λ). It results in high impedance (Hi Z) at the far ends *reflected* as low impedance (Lo Z) at the end connected to the transmission line. This causes the antenna to have a large current node at the center and large voltage nodes at the ends, resulting in maximum radiation.

9-1.2 The Elementary Doublet (Hertzian Dipole)

The doublet is a theoretical antenna shorter than a wavelength (Figure 9-3*a*). It is used as a standard to which all other antenna characteristics can be compared.

The field strength of this antenna can be calculated as follows:

$$E = \frac{60\pi \, Le \, I}{\lambda r} \sin \theta \qquad \text{(9-2)}$$

E = magnitude of field strength (μs/m)

r = distance

Le = antenna length

I = current amplitude

Θ = the angle of the axis of the wire and the point of maximum radiation

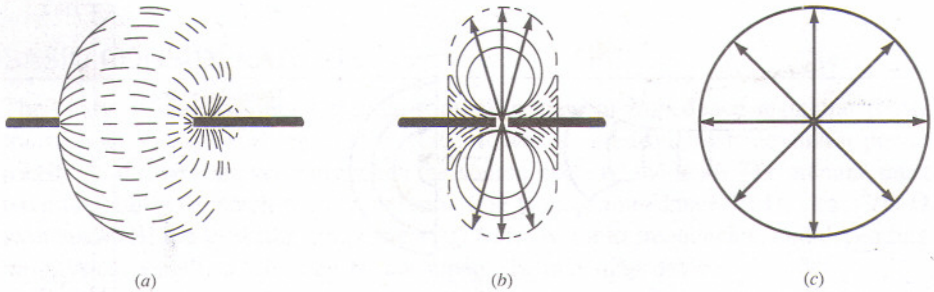

FIGURE 9-3 Radiation pattern of the elementary doublet (Hertzian dipole). (*a*) Side view; (*b*) angle of maximum radiation; (*c*) top view.

As shown in Figure 9-3*b*, the radiation is a double circular pattern, with maximum radiation at 90° to the axis of the wire.

9-2 WIRE RADIATOR IN SPACE

The following sections discuss the characteristics of antennas isolated from surfaces which will alter or change their radiation patterns and efficiency.

9-2.1 Current and Voltage Distribution

When an RF signal voltage is applied at some point on an antenna, voltage and current will result at that point. Traveling waves are then initiated, and standing waves may be established, which means that voltage and current along the antenna are out of phase.

The radiation pattern depends chiefly on the antenna length measured in wavelengths, its power losses, and the terminations at its end (if any). In addition, the thickness of the antenna wire is of importance. For this discussion such antennas may be assumed to be lossless and made of wire whose diameter is infinitely small.

Figure 9-4 shows the voltage and current distribution along a half-wave dipole. We can recognize the similarity to the distribution of voltage and current on a section of $\frac{1}{4}$-λ transmission line open at the far end. These voltage and current characteristics are duplicated every $\lambda/2$ length, along the antenna (Figure 9-5).

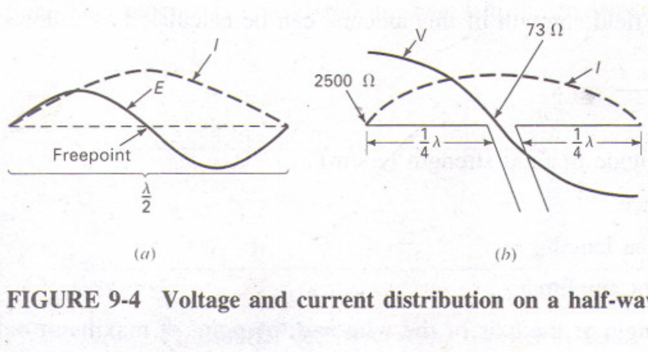

FIGURE 9-4 Voltage and current distribution on a half-wave dipole.

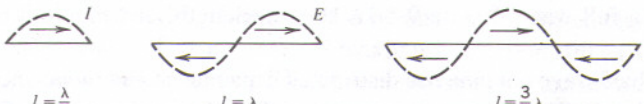

FIGURE 9-5 Current distribution on resonant dipoles.

By referring to Figure 9-4, it will become apparent that to connect a transmission line to this antenna configuration, we must observe the impedance at the connection points. The impedance varies along the length of the antenna, being *highest* where the current is *lowest,* and *lowest* where the current is *highest* (at the center). At the center of a half-wave antenna the impedance is approximately 73 Ω and increases to about 2500 Ω at either end.

In order to achieve maximum power transfer, this antenna must be connected to a 72-Ω transmission line. This method of connection, the transmission line to the antenna, is sometimes referred to as center or current fed.

9-2.2 Resonant Antennas, Radiation Patterns, and Length Calculations

Basic resonance theory has taught us that a high Q resonant circuit has a very narrow bandwidth. The same holds true for the resonant antenna. The narrow bandwidth establishes the useful limits for this type of radiator. This will be fully covered in Section 9-6.2.

The radiation pattern of a wire radiator in free space depends mainly on its length. Refer to Figure 9-6*a* for the standard figure eight pattern of a half wave. Figure

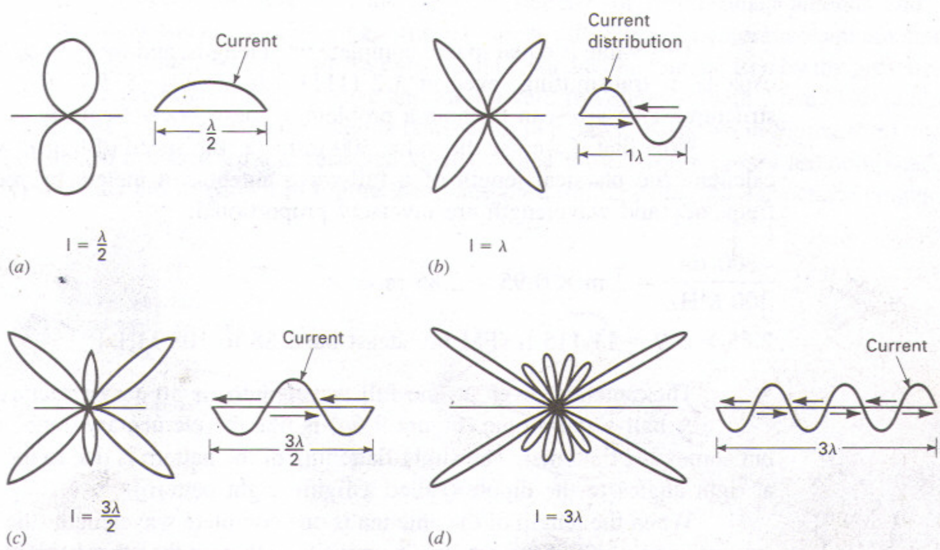

FIGURE 9-6 Radiation patterns of various resonant dipoles.

9-6*b* shows a full wave, Figure 9-6*c* a 1½ wavelength, and Figure 9-6*d* three wavelengths.

The half-wave antenna has distributed capacitance and inductance and acts like a resonant circuit. The voltage and current will not be in phase. If an RF voltmeter is connected from the end of the antenna to ground, a large voltage will be measured. If the meter lead is moved toward the center, the voltage will diminish.

The length of the antenna can be calculated using Equation (9-3) (the velocity factor of wire is ≈95 percent compared to air, which is 1). Then

$$L = \frac{\text{vel}}{f} \tag{9-3}$$

EXAMPLE 9-1 Determine the length of an antenna operating at a frequency of 500 kHz.

SOLUTION

$$L = \frac{\text{vel}}{f} \times 0.95\ (V_f)$$

where L = length in meters

vel = speed of light 3×10^8 m/s (or 300 m/μs)

f = frequency in hertz

V_f = velocity factor 0.95 (sometimes called end effect)

$$\text{L} = \frac{3 \times 10^8}{f} \times 0.95 = \frac{3 \times 10^8}{5 \times 10^5} \times 0.95 = 570 \text{ m}$$

Converted to feet = 3.9 × 570 = 2244 ft

This value is equal to one complete wavelength, and we can see that an antenna capable of transmitting, even at $\lambda/2$ (1111.5 ft) or $\lambda/4$ (555.75 ft), can be quite a structure. This size can become a problem at these lower frequencies.

Note that if we use the value 300 m/mHz (the speed of light), we can quickly calculate the physical length of a full-wave antenna in meters by recognizing that frequency and wavelength are inversely proportional.

$$\frac{300/\mu\text{s}}{100 \text{ MHz}} = 3 \text{ m} \times 0.95 = 2.85 \text{ m}$$

$2.85 \times 3.9 = 11.115$ ft (FM broadcast band 88 to 108 MHz)

This antenna, even at one full wavelength, is an easy structure to erect.

A half-wave dipole (Figure 9-6*a*) is like the elementary doublet (Figure 9-3), but somewhat flattened. The slight flattening of the pattern is due to the reinforcement at right angles to the dipole (called a figure eight pattern).

When the length of the antenna is one complete wavelength, the polarity of the current in one-half of the antenna is opposite to that on the other half (Figure 9-6*b*). As a result of these out-of-phase currents, the radiation at right angles from this antenna will be zero. The field radiated by one-half of the antenna alters the field radiated by the other half. A direction of maximum radiation still exists, but it is no longer at right angles to the antenna. For a full-wave dipole, maximum radiation will be at 54° to the antenna. This process has now generated extra *lobes*. There are four in this situation.

As the length of the dipole is increased to three half wavelengths, the current distribution is changed to that of Figure 9-6*c*. The radiation from one end of the antenna adds to that from the other, at right angles, but both are *partially* canceled by the radiation from the center, which carries a current of opposite polarity. There is radiation at right angles to the antenna, but it is not reinforced; therefore lobes in this direction are *minor lobes*. The direction of *maximum* radiation, or of *major lobes,* is closer to the direction or axis of the dipole itself, as shown in Figure 9-6*d*.

As we continue increasing the length, we increase the number of lobes, and the direction of the major lobes is brought closer or more aligned in the direction of the dipole. By looking closely at the patterns emerging, we can see that there are just as many radiation lobes on one side of the dipole as there are current lobes of both polarities. The 1½ ($3/2\ \lambda$) wavelength has three radiation lobes on each side, and a 3-λ antenna has six (Figure 9-6*d*).

9-2.3 Nonresonant Antennas (Directional Antennas)

A nonresonant antenna, like a properly terminated transmission line, produces no standing waves. They are suppressed by the use of a correct termination resistor and no power is reflected, ensuring that only forwarding traveling waves will exist. In a correctly matched transmission line, all the transmitted power is dissipated in the terminating resistance. When an antenna is terminated as in Figure 9-7*a*, about two-thirds of the forward power is radiated; the remainder is dissipated in the antenna.

As seen in Figure 9-7, the radiation patterns of the resonant antenna and a nonresonant one are similar except for one major difference. The nonresonant antenna is *unidirectional*. Standing waves exist on the resonant antenna, caused by the presence of both a reflected traveling wave and the forward traveling incident wave. The radiation pattern of the resonant antenna consists of two parts, as shown in Figure 9-8*a* and *b*, due to the forward and reflected waves. When these two processes are combined, the results are as shown in Figure 9-8*c*, and the familiar *bidirectional* pattern results.

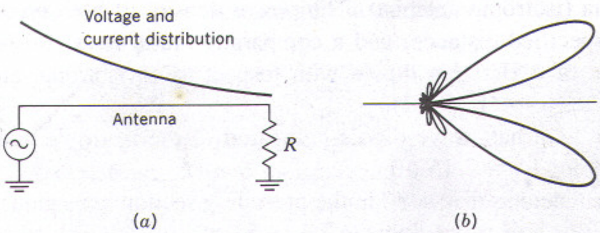

FIGURE 9-7 Nonresonant antenna. (*a*) Layout and current distribution; (*b*) radiation pattern.

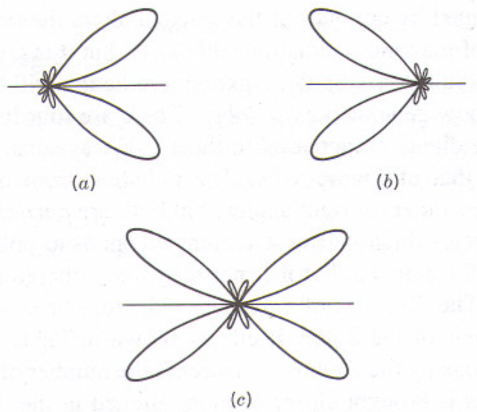

FIGURE 9-8 Synthesis of resonant antenna radiation pattern. (*a*) Due to forward wave; (*b*) due to reverse wave; (*c*) combined pattern.

9-3 TERMS AND DEFINITIONS

The preceding section showed that the radiation pattern of a wire antenna is complex, and some way must be found of describing and defining it. Again, something must be said about the effective resistance of antennas, their polarization and the degree to which they concentrate their radiation. We will now describe and define a number of important terms used in connection with antennas and their radiation patterns.

9-3.1 Antenna Gain and Effective Radiated Power

Certain types of antennas focus their radiation pattern in a specific direction, as compared to an omnidirectional antenna.

Another way of looking at this concentration of the radiation is to say that some antennas have gain (measured in decibels).

Directive gain *Directive gain* is defined as the ratio of the power density in a particular direction of one antenna to the power density that would be radiated by an omnidirectional antenna (isotropic antenna). The power density of both types of antenna is measured at a specified distance, and a comparative ratio is established.

The gain of a Hertzian dipole with respect to an isotropic antenna = 1.5:1 power ($1.5\ (10 \log_{10}) = 1.76$ dB).

The gain of a half-wave dipole compared to the isotropic antenna = 1.64:1 power ($1.64\ (10 \log_{10}) = 2.15$ dB).

The wire antennas discussed in the preceding section have gains that vary from 1.64 (2.15 dB) for a half-wave dipole to 7.1 (8.51 dB) for an eight-wave dipole. These figures are for resonant antennas in free space. Similar nonresonant antennas have gains of 3.2 (5.05 dB) and 17.4 (12.4 dB) respectively. Two sets of characteristics can be obtained from the previous information:

1. The longer the antenna, the higher the directive gain.
2. Nonresonant antennas have higher directive gain than resonant antennas.

Directivity and power gain (ERP) Another form of gain used in connection with antennas is *power gain*. Power gain is a comparison of the *output* power of an antenna in a certain direction to that of an *isotropic* antenna. The gain of an antenna is a power ratio comparison between an omnidirectional and unidirectional radiator. This ratio can be expressed as:

$$A(\text{dB}) = 10 \log_{10}\left(\frac{P_2}{P_1}\right) \tag{9-4}$$

where $A(\text{dB})$ = antenna gain in decibels
P_1 = power of unidirectional antenna
P_2 = power of reference antenna

EXAMPLE 9-2 A half-wave dipole antenna is capable of radiating 1-kW and has a 2.15-dB gain over an isotropic antenna. How much power must be delivered to the isotropic (omnidirectional) antenna, to match the *field-strength* directional antenna?

SOLUTION

$$A(\text{dB}) = 10 \log_{10}\left(\frac{P_2}{P_1}\right)$$

$$2.15 = 10 \log_{10}\left(\frac{P_2}{1000}\right)$$

$$0.215 = \log_{10}\left(\frac{P_2}{1000}\right)$$

$$10^{0.215} = \left(\frac{P_2}{1000}\right)$$

$$1.64 = \left(\frac{P_2}{1000}\right)$$

$$P_2 = 1.64 \times 1000$$

$$P_2 = 1640 \text{ W}$$

Another set of terms is also used in describing the performance of a transmitting system. One term is *effective radiated power* (*erp*). It applies to the field gain of the antenna and the efficiency of the transmitter.

EXAMPLE 9-3 If an antenna has a field gain (expressed in voltage) of 2, and the transmitter has an overall efficiency of 50 percent (the circuit and transmission line losses) then, if a 1-kW signal is fed to the finals, this will result in 500 W being fed to the antenna. What is the erp?

SOLUTION

$$\text{erp} = P_0 \times \text{field gain}^2$$

$$\text{erp} = 500 \times 2^2$$

$$\text{erp} = 2000 \text{ W}$$

9-3.2 Radiation Measurement and Field Intensity

The voltages induced in a receiving antenna are very small, generally in the microvolt range. Field strength measurements are thus given in microvolts per meter.

Field intensity *The field strength (field intensity) of an antenna's radiation, at a given point in space, is equal to the amount of voltage induced in a wire antenna 1 m long, located at that given point.*

The field strength, or the induced voltage, is affected by a number of conditions such as the time of day, atmospheric conditions, and distance.

9-3.3 Antenna Resistance

Radiation resistance is a hypothetical value which, if replaced by an equivalent resistor, would dissipate exactly the same amount of power that the antenna would radiate.

Radiation resistance *Radiation resistance is the ratio of the power radiated by the antenna to the square of the current at the feed point.*

Antenna losses and efficiency In addition to the energy radiated by an antenna, power losses must be accounted for. Antenna losses can be caused by ground resistance, corona effects, imperfect dialectric near the antenna, energy loss due to eddy currents induced into nearby metallic objects, and I^2R losses in the antenna itself. We can combine these losses and represent them as shown in Equation (9-5).

$$P\text{in} = P_d + P_{rad} \tag{9-5}$$

where P_{in} = power delivered to the feed point

P_d = power lost

P_{rad} = power actually radiated

Converting Equation (9-5) to I^2R terms, we may state the equation as follows.

$$I^2R_{in} = I^2R_d + I^2R_{rad}$$
$$R_{in} = R_d + R_{rad}$$

From this expression we can now develop an equation for calculating antenna efficiency.

$$n = \frac{R_{rad}}{R_{rad} + R_d} \times 100\% \tag{9-6}$$

R_d = antenna resistance

R_{rad} = antenna radiation resistance

Low- and medium-frequency antennas are least efficient because of difficulties in achieving the proper physical (resonant) length. These antennas can approach efficiencies of only 75 to 95 percent. Antennas at higher frequencies can easily achieve values approaching 100 percent. Radiation resistance values may vary from a few ohms to several hundred ohms depending on the choice of feed points and physical and electrical characteristics.

9-3.4 Bandwidth, Beamwidth, and Polarization

Bandwidth, beamwidth, and *polarization* are three important terms dealing respectively with the operating frequency range, the degree of concentration of the radiation pattern, and the space orientation of the radiated waves.

Bandwidth The term bandwidth refers to the range of frequencies the antenna will radiate effectively; i.e., the antenna will *perform satisfactorily* throughout this range of frequencies. When the antenna power drops to ½ (3 dB), the upper and lower extremities of these frequencies have been reached and the antenna no longer *performs satisfactorily*.

Antennas that operate over a wide frequency range and still maintain satisfactory performance must have compensating circuits switched into the system to maintain impedance matching, thus ensuring no deterioration of the transmitted signals.

Beamwidth The *beamwidth* of an antenna is described as the angles created by comparing the half-power points (3 dB) on the main radiation lobe to its maximum power point. In Figure 9-9, as an example, the *beam angle* is 30°, which is the sum of the two angles created at the points where the *field strength* drops to 0.707 (field strength is measured in μ/V/m) of the maximum voltage at the center of the lobe. (These points are known as the half-power points.)

Polarization Polarization of an antenna refers to the direction in space of the *E* field (electric vector) portion of the electromagnetic wave being radiated (Figure 9-10) by the transmitting system.

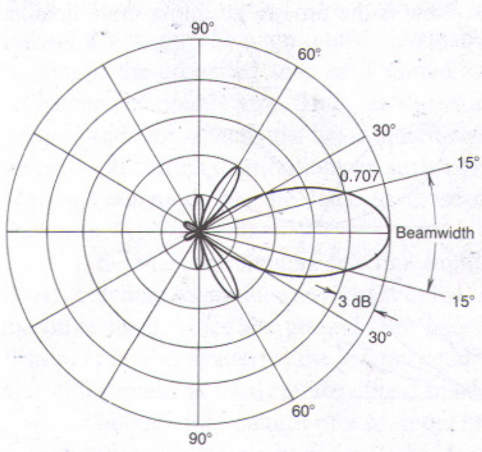

FIGURE 9-9 Beamwidth.

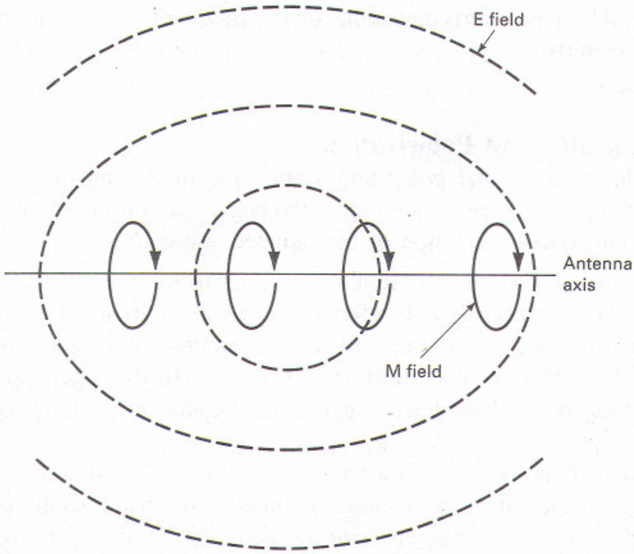

FIGURE 9-10 Polarization of the antenna showing *E* and *M* fields.

Low-frequency antennas are usually vertically polarized because of ground effect (reflected waves, etc.) and physical construction methods. High-frequency antennas are generally horizontally polarized. Horizontal polarization is the more desired of the two because of its rejection to noise made by people, which is, for the most part, vertically polarized.

9-4 EFFECTS OF GROUND ON ANTENNAS

The interaction of ground with antenna impedance and radiation characteristics has been touched on previously. Now is the time to go into a more detailed discussion of the interaction (see Figure 9-11).

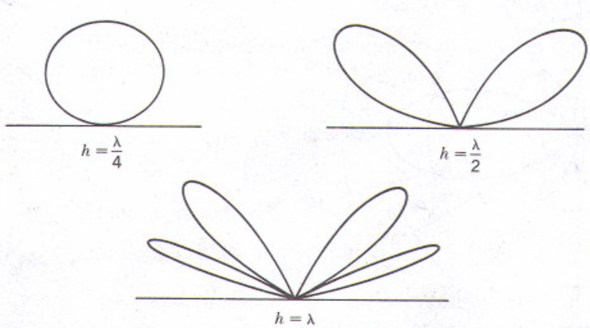

FIGURE 9-11 Radiation patterns of an ungrounded half-wave dipole located at varying heights above the ground.