

The Evolution of Antenna Technology

History, dipoles, and loops.

This article is a historical review of the introduction, development, and advancement of antenna technology, starting with the spark-gap transmission and reception by Hertz in the late 1880s. The article underscores some of the basic antenna designs that contributed to the evolution of antenna technology, especially linear dipoles and loops, which were part of Hertz's 1886 spark-gap dipole transmitter and loop receiver experiment, and also describes some of their basic radiation characteristics.

INTRODUCTION

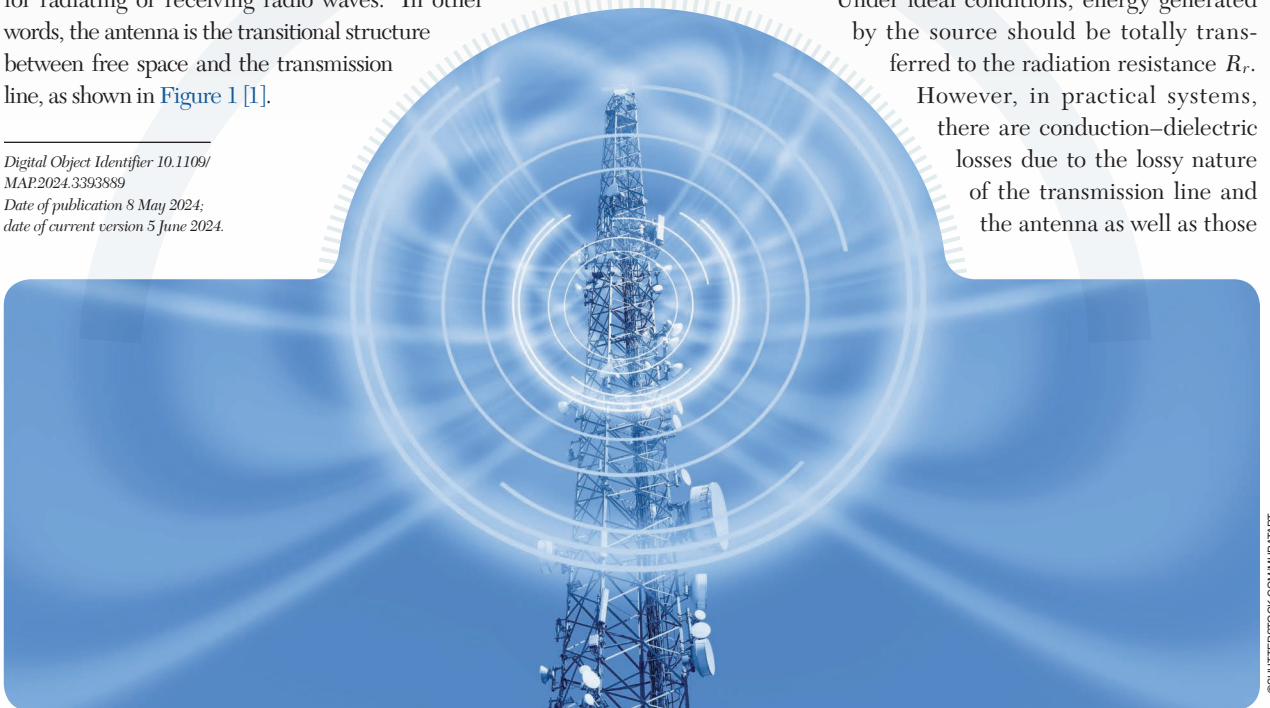
An antenna is defined by Webster's Dictionary as "a usually metallic device (as a rod or wire) for radiating or receiving radio waves." The *IEEE Standard Definitions of Terms for Antennas* (IEEE Std 145-1983) defines the antenna or aerial as "a means for radiating or receiving radio waves." In other words, the antenna is the transitional structure between free space and the transmission line, as shown in Figure 1 [1].

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The transmission line may take the form of a coaxial line or a waveguide, and it is used to transport electromagnetic energy from the transmitting source to the antenna or, conversely, from the antenna to the receiver. In the former case, we have a *transmitting* antenna and in the latter a *receiving* antenna. A Thevenin equivalent of the transmission line and the antenna system in the transmitting mode of Figure 1 is displayed in Figure 2, where the source is represented by an ideal generator with internal impedance Z_g , the transmission line is represented by a line with characteristic impedance Z_c , and the antenna is represented by a load Z_A [$Z_A = (R_L + R_r) + jX_A$]. The resistance R_r , referred to as the radiation resistance, is used to represent radiation by the antenna, while the reactance X_A is used to represent the imaginary part of the impedance associated with radiation by the antenna.

Under ideal conditions, energy generated by the source should be totally transferred to the radiation resistance R_r .

However, in practical systems, there are conduction–dielectric losses due to the lossy nature of the transmission line and the antenna as well as those



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due to mismatch (reflection) losses at the interface between the line and the antenna. Taking into account the internal impedance of the source and neglecting line and mismatch (reflection) losses, maximum power is delivered to the antenna under conjugate matching. Along with the traveling waves from the source toward the antenna, the reflections form constructive and destructive interference patterns, referred to as *standing waves*, inside the transmission line, which represent pockets of energy concentrations and storage and are typical of resonant devices. A typical standing wave pattern is shown with a dashed line in Figure 2 [1], [2]. If the reflections are not minimized and the antenna system is not properly matched, the transmission line could act to a large degree as an energy-storage element instead of a wave-guiding and energy-transporting device.

According to John D. Kraus, an author and pioneer of antenna technology, “antennas are the electronic eyes and ears of the world.” As the eyes and ears are critical to humans for efficient communication and activity, antennas are critical to wireless communication systems for transmitting and receiving information efficiently. Since the days of modern antenna technology, dating back to the 1920s with the introduction of the Yagi-Uda array [1], antennas have undergone a revolution and played pivotal roles in the NASA space program to allow humans to land on the moon in 1969 and send messages, photos, and videos of the Neil Armstrong walk on the moon. Today, antennas are critical devices that permit

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wireless communication systems to send text, photos, messages, e-mails, news, and other information even from cell phones, from anyone to anyone in the world. Some of these personal wireless devices, from the initial era of the 1980s to the most advanced and modern devices, are shown in Figure 3. While initially the antennas were external, eventually they were moved/embedded internally, to avoid breakage and

improve their visual appearance. Both designs are exhibited in Figure 3 [1].

HISTORICAL INTRODUCTION AND ADVANCEMENT

The history of antennas [3] dates back to James Clerk Maxwell, and he first published his work in 1873 [4]. Maxwell unified the theories of electricity and magnetism, and he eloquently represented their relations through a set of profound equations best known as *Maxwell's equations*. Maxwell also showed that light

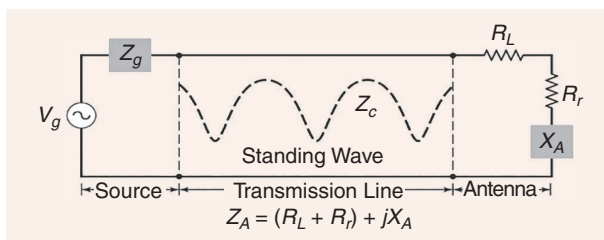


FIGURE 2. Transmission-line Thevenin equivalent of an antenna in transmitting mode. (Source: [1].)

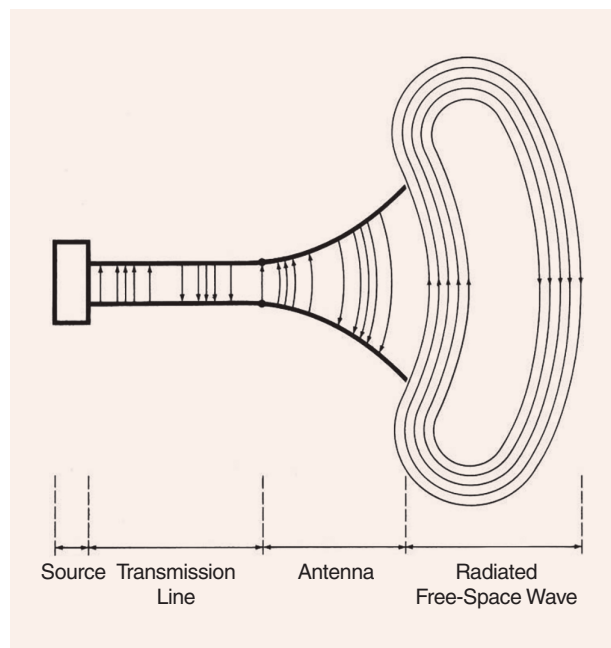


FIGURE 1. The antenna as a transitional device. (Source: [1].)



FIGURE 3. Examples of external and embedded/internal antennas used in commercial cellular and CB radios. (Source: [1].)

was electromagnetic and that both light and electromagnetic waves travel by wave disturbances of the same speed. In 1886, Prof. Heinrich Rudolf Hertz, illustrated in Figure 4(a), demonstrated the first wireless electromagnetic system. He was able to produce in his laboratory a spark in the gap of a transmitting linear dipole, which was then detected as a spark in the gap of a nearby resonant loop, as displayed in Figure 4(b).

Guglielmo Marconi [see Figure 5(a)] in 1901 was able to send signals over large distances using the wireless transmitting station at Poldhu, Cornwall, England, shown in Figure 5(b). It was the first transatlantic transmission, transmitting from Poldhu in England to St. John's, Newfoundland. His ground-based spark transmitter was connected to an inverted conical wire antenna array consisting of 200 wires suspended from horizontal masts supported by four poles, as illustrated in Figure 5(b).

Since the inception of Marconi's transmitter in 1901 and through the 1940s, antenna technology was primarily centered on wire-related radiating elements and frequencies up

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to about the ultrahigh frequency (UHF) range. Modern antenna technology, including the introduction of new elements (such as waveguide apertures, horns, and reflectors), was launched during World War II; most of this work was included in the book by Silver [5]. A major factor that contributed to this new era was the invention of microwave sources (such as the klystron and magnetron) with frequencies of 1 GHz and higher. The antenna design that may have been the beacon of

modern antenna technology, especially array configurations, was the Yagi-Uda array of the 1920s, as illustrated in Figure 6, whose first English publication appeared in *IRE Proceedings* in June 1928. This unique and clever Yagi-Uda array design was recognized in 1984 by IEEE (formerly AIEE and IRE) on its centennial year for its impact and future advancements of antenna technology.

The widespread interest in antennas is reflected by the large number of books written on the subject [6], which can be classified into four categories: fundamental, handbooks, measurements, and specialized. This outstanding collection of books reflects the popularity and advancements of antenna technology, especially since the 1950s. A partial list of authorship on the antenna subject is included in [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], and [44]; some of the other books may now be out of print.

While World War II launched a new era in antennas, a major impact on the advances of modern antenna technology may have been the innovations and

breakthroughs in computer architecture and technology during the 1960s through the 1990s. These advancements in simulations and computations, which led to the plethora of simulation software, had an even greater influence on antenna engineering into the 21st century and beyond. Starting around the early 1960s, numerical methods were introduced that permitted previously intractable complex antenna configurations to be analyzed, designed, and advanced. In addition, low- and high-frequency asymptotic methods, such as the moment method, finite-difference time-domain method, finite-element method, and the geometrical and physical theories of diffraction, were introduced and contributed significantly to the maturity and advancement of antenna design and technology [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57]. Today many

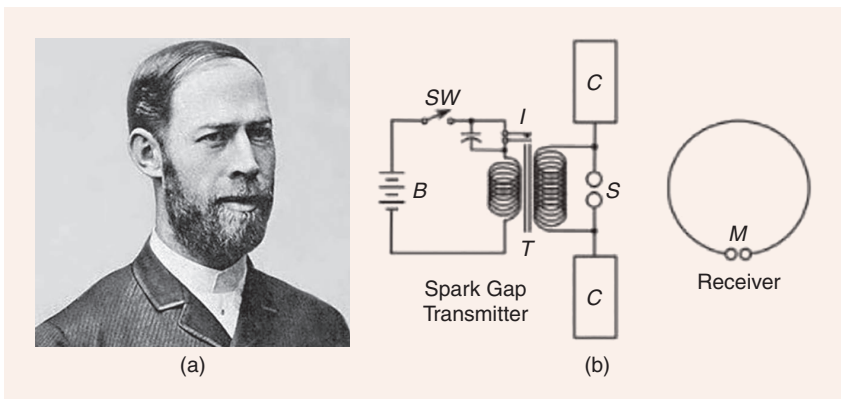


FIGURE 4. (a) Heinrich Rudolf Hertz (1857–1894) and (b) Hertz's spark-gap dipole transmitter and loop receiver.

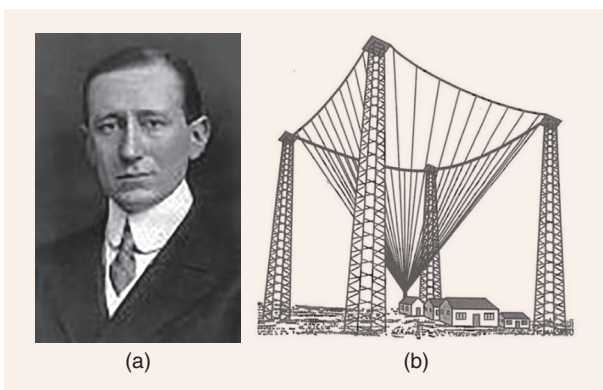


FIGURE 5. (a) Guglielmo Marconi (1874–1937) and (b) his square inverted conical wire antenna array.

wireless communication system successes rely on the design and performance of the antennas. Analysis and design methods are such that antenna system performance can be predicted with remarkable accuracy. Today, many antenna designs proceed directly from the initial design stage to the prototype without intermediate testing. The confidence in performance and success has increased tremendously.

ANTENNA TYPES

Most antenna elements, especially prior to World War II, were of the wire type:

- They were long wires, dipoles, loops, helices, rhombuses, fans, etc. They were used either as single elements or in arrays. Such elements are familiar to the layman because they are seen virtually everywhere—on automobiles, buildings, ships, aircraft, spacecraft, etc.

During and after World War II, especially with the innovation and introduction of microwave sources such as klystrons and magnetrons, many other radiators were put into service. This created a need for better understanding and optimization of their radiation characteristics [35]. Many of these antennas were of the aperture type and operated in the microwave frequency region:

- They included open-ended waveguides, slots, horns, reflectors, lenses, etc. They have been used for communication, radar, remote sensing, and deep space applications both on airborne and earth-based platforms. Antennas of this type are very useful for aircraft and spacecraft applications because they can be very conveniently flush-mounted on the skin of the aircraft or spacecraft.

Prior to the 1950s, antenna designs had pattern and impedance characteristics with bandwidths not much greater than about 2:1. A breakthrough in antenna bandwidth was created, which extended the maximum bandwidth to as great as 40:1 or more, by the introduction of antenna designs whose geometries were specified by angles instead of linear dimensions; ideally they had an infinite bandwidth. Therefore, these unique and clever designs are referred to as *frequency-independent antennas*. These antennas are primarily used in the 10–10,000-MHz region in a variety of applications, including TV, point-to-point communications, feeds for reflectors and lenses, and many others. This class of antennas is discussed in [36].

It was not until almost 20 years later that a fundamental and new radiating element was introduced, which has received a lot of attention and many applications since its inception. This occurred in the late 1960s/early 1970s when the microstrip or patch antenna was invented, reported, and implemented. This new microstrip/patch element is simple, lightweight, inexpensive, low profile, and conformal to the surface. These antenna

These advancements in simulations and computations, which led to the plethora of simulation software, had an even greater influence on antenna engineering into the 21st century and beyond.

configurations and designs are discussed in detail in [37]. Major advances in millimeter-wave antennas have been made in recent years, including integrated antennas, in which active and passive circuits are combined with the radiating elements in one compact unit (monolithic form). These antennas are discussed in [38].

The success in the exploration of outer space has resulted in the advancement of antenna technology. Because of the need to communicate over great distances, unique and sophisticated antenna designs were introduced and used to transmit and receive signals that

travel millions of miles. A very common antenna form for such an application is the parabolic reflector, which has been built with diameters of 305 m or even larger. Such large dimensions are needed to achieve the high gain required to transmit or receive signals after millions of miles of travel. Another form of reflector, although not as common as the parabolic type, is the corner reflector.

Another design of electromagnetic radiators involves lenses, which are primarily used to collimate incident divergent

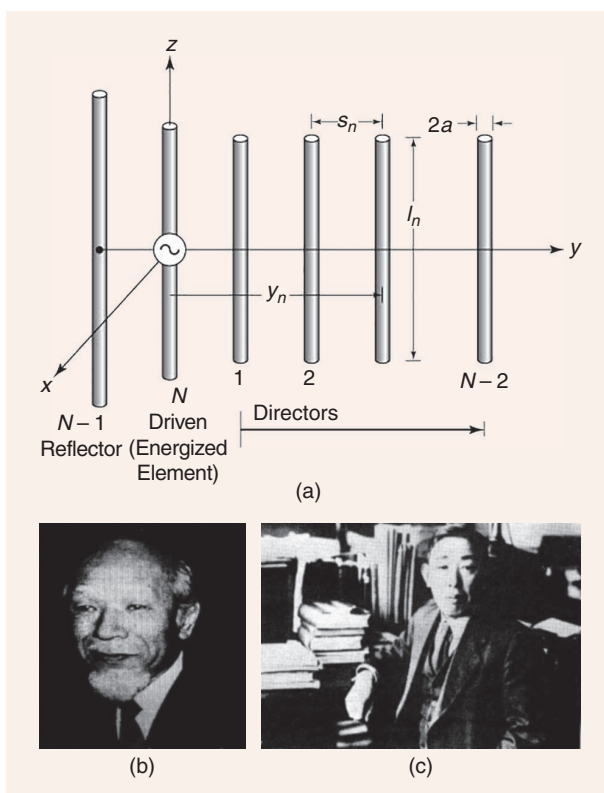


FIGURE 6. The Yagi-Uda antenna configuration. (a) The Yagi-Uda array. (Source: [1].) (b) H. Yagi (1886–1976). (c) S. Uda (1896–1976).

energy to prevent it from spreading in undesired directions. Their design principles and functioning are the same as those of human eyes. By choosing the appropriate materials and properly shaping the geometrical configuration of the lenses, they can transform various forms of divergent energy into plane waves. They can be used in most of the same applications as are the parabolic reflectors, especially at higher frequencies. Their dimensions and weight become exceedingly large at lower frequencies.

Many applications require radiation characteristics that may not be achievable by a single element. However, it may be possible that an aggregate of radiating elements in an electrical and geometrical arrangement, referred to as *an array*, will provide the desired radiation characteristics. The arrangement of the array may be such that the radiation from the elements adds up constructively to give a radiation maximum in a particular direction or directions and a destructively minimum one in others, or otherwise as desired. Usually the term *array* is reserved for an arrangement in which the individual radiators are separate. However, the same term is also used to describe an assembly of radiators mounted on a continuous structure.

Arrays are the most versatile antenna systems. They find wide applications not only in many space-borne systems but in many earthbound missions as well. The individual elements of an array are almost always identical; this is not necessary, but it is often more convenient, simpler, and more practical. With arrays, it is practical not only to synthesize basically any desired amplitude radiation pattern, but also to have it scan the main lobe in any desired direction by controlling the relative phase excitation between the elements. This is most convenient for applications where the antenna system is not readily accessible, especially for space-borne

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missions. The beamwidth of the main lobe along with the sidelobe level can be controlled by the relative amplitude distribution (excitation) between the elements of the array. In fact, a tradeoff between the beamwidth and the sidelobe level is based on the amplitude distribution. Advances in array technology have been reported in [39], [40], [41], [42], [43], and [44]. A new antenna array design, referred to as a

smart antenna [44], based on technology of the 1970s and 1980s, sparked intense interest, especially in adaptive array beamforming for wireless applications. While the linear dipole and loop, the two elements used by Hertz in his 1886 spark-gap experiment—the dipole being the transmitting element and the loop the receiving element, as illustrated in Figure 4(b)—are discussed in this article, some of the other classic single elements and arrays will be reviewed in a series of articles to appear in future issues of *IEEE Antennas and Propagation Magazine*.

LINEAR WIRE ANTENNAS

Wire antennas, linear or curved, are some of the oldest, simplest, most inexpensive, and in many cases the most versatile for many applications. In fact, a linear dipole, which served as the transmitting element, was part of Hertz's spark-gap system in 1886. Thus, it should not come as a surprise that we begin the presentation by considering some of the oldest, simplest, and most basic configurations. The simplest radiating element is a linear wire, as shown in Figure 7(a). The orthogonal spherical coordinate system and associated electric field components radiated by an antenna (E_r , E_θ , E_ϕ) are illustrated in Figure 7(b).

The space surrounding an antenna is usually subdivided into three basic regions [1]:

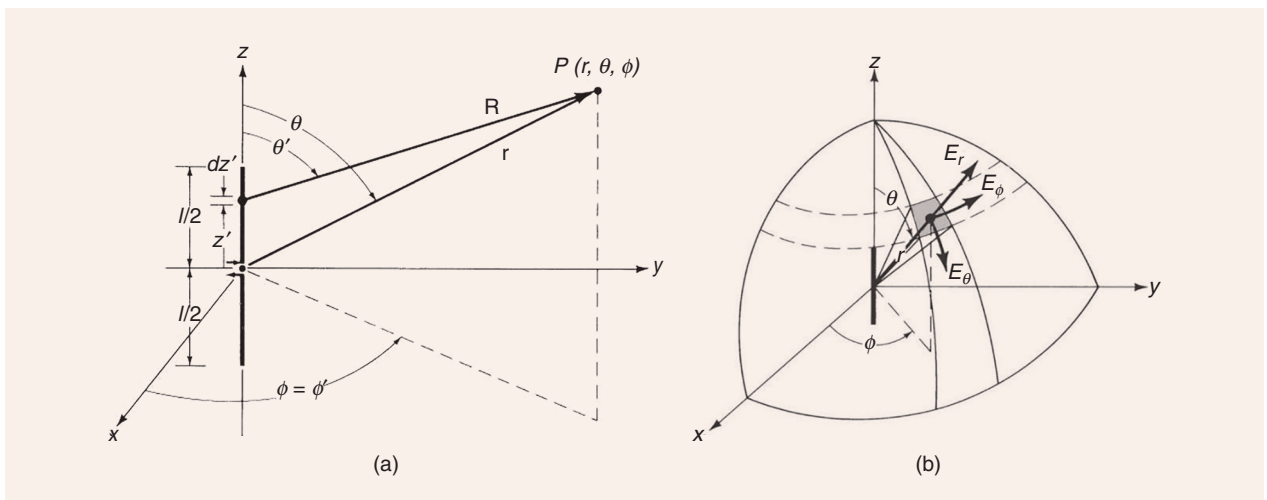


FIGURE 7. (a) Linear wire and (b) the associated electric field components and orientation on a spherical surface. (Source: [1].)

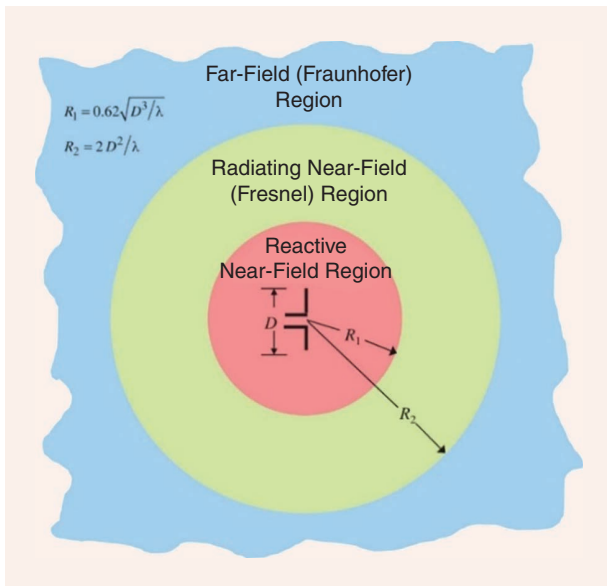


FIGURE 8. Field regions surrounding an antenna. (Source: [1].)

- 1) reactive near field
- 2) radiating near field (also known as Fresnel region)
- 3) far field (also known as Fraunhofer region).

These are shown in Figure 8. These regions are designated as such to identify the field structure in each. Although no abrupt changes in the field configurations occur or are noted as the boundaries are crossed, there are some distinct differences among them. The boundaries separating these regions are not unique, although various criteria have been established and are commonly used to identify the different regions and their boundaries [1].

The *far-field (Fraunhofer) region* is usually the one of most interest, and it is defined as “that region of the field of an antenna where the angular field distribution is

essentially independent of the distance from the antenna. If the antenna has a maximum overall dimension D , the far-field region is commonly the space at distances greater than $2D^2/\lambda$ from the antenna, λ being the wavelength. For an antenna focused at infinity, the far-field region is sometimes referred to as the Fraunhofer region on the basis of analogy to optical terminology” [1]. In this region, the field components are essentially transverse electromagnetic to the radial r direction, TEM^r (basically only E_θ and E_ϕ as E_r is very small compared to the other two; so small it is usually assumed to be negligible, $E_r \approx 0$), and the angular distribution is independent of the radial distance. The inner boundary is taken to be the radial distance $R_2 = 2D^2/\lambda$, as shown in Figure 8, and the outer one is at infinity.

As indicated previously, the linear dipole is one of the two elements (dipole as transmitting and loop as receiving) that Hertz used in his 1886 experiment [Figure 4(b)] that demonstrated the transmission and reception of an electromagnetic wave. The most commonly used antenna is the half-wavelength ($l = \lambda/2$) dipole. Because its radiation resistance is $R_r = 73 \Omega$, which is very near the $50\text{-}\Omega$ or $75\text{-}\Omega$ characteristic impedances of some practical transmission lines, its matching to the transmission line is simplified, especially at resonance.

Based on an ideal sinusoidal current distribution, its 3D far-field normalized amplitude pattern is plotted in Figure 9(a). The 2D pattern is depicted in Figure 9(b), where its ideal pattern is compared with sinusoidal angular approximations. The direction of the electric field is in the θ direction (the E_θ vertical component); thus, the element is vertically polarized. As the length of the dipole increases beyond one wavelength ($l > \lambda$), the number of lobes begins to increase. The normalized power pattern for a dipole with $l = 1.25\lambda$ is displayed in Figure 10, which shows, once it exceeds an overall length of one wavelength, the

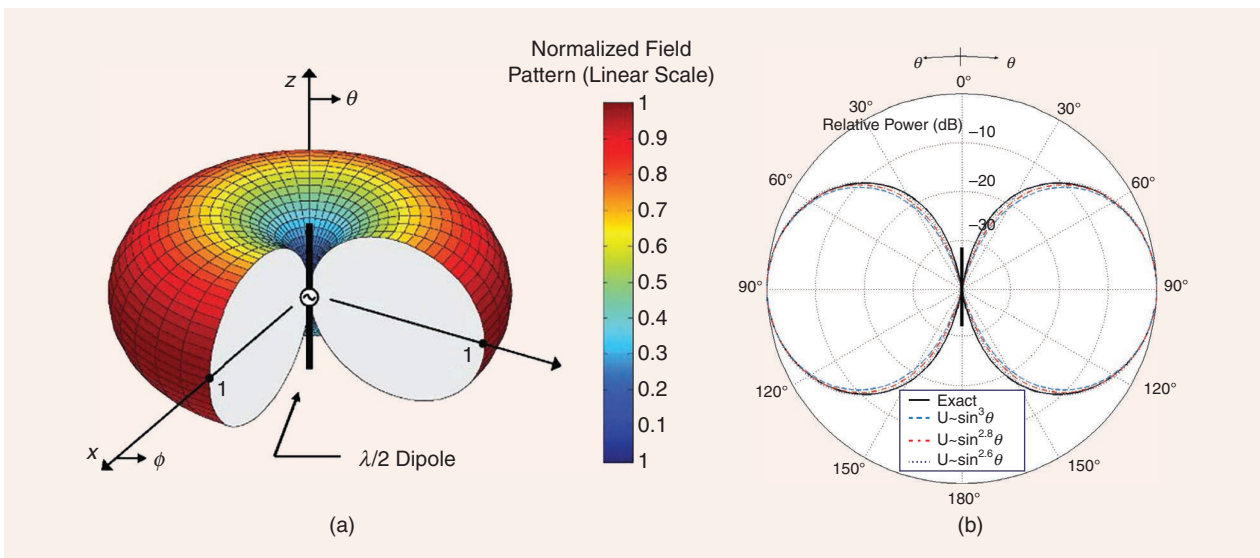


FIGURE 9. 3D and 2D patterns of a $\lambda/2$ dipole. (a) 3D pattern of a $\lambda/2$ dipole. (b) Comparison of 2D patterns for a $\lambda/2$ dipole. (Source: [1].)

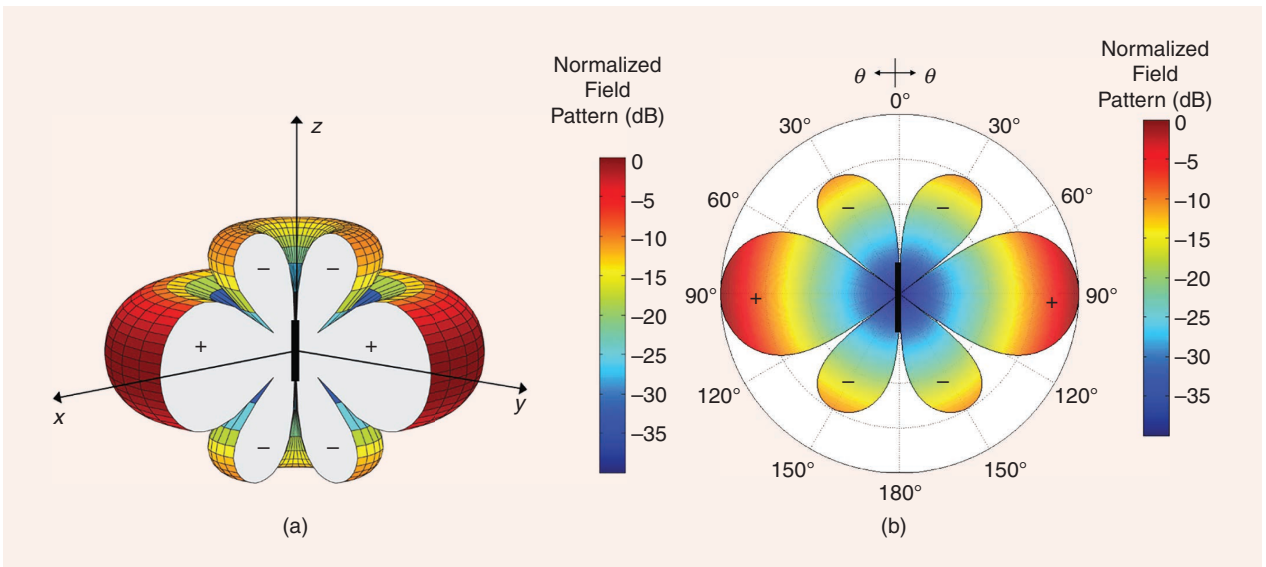


FIGURE 10. (a) 3D and (b) 2D amplitude patterns for a thin dipole of $l = 1.25\lambda$ and sinusoidal current distribution. (Source: [1].)

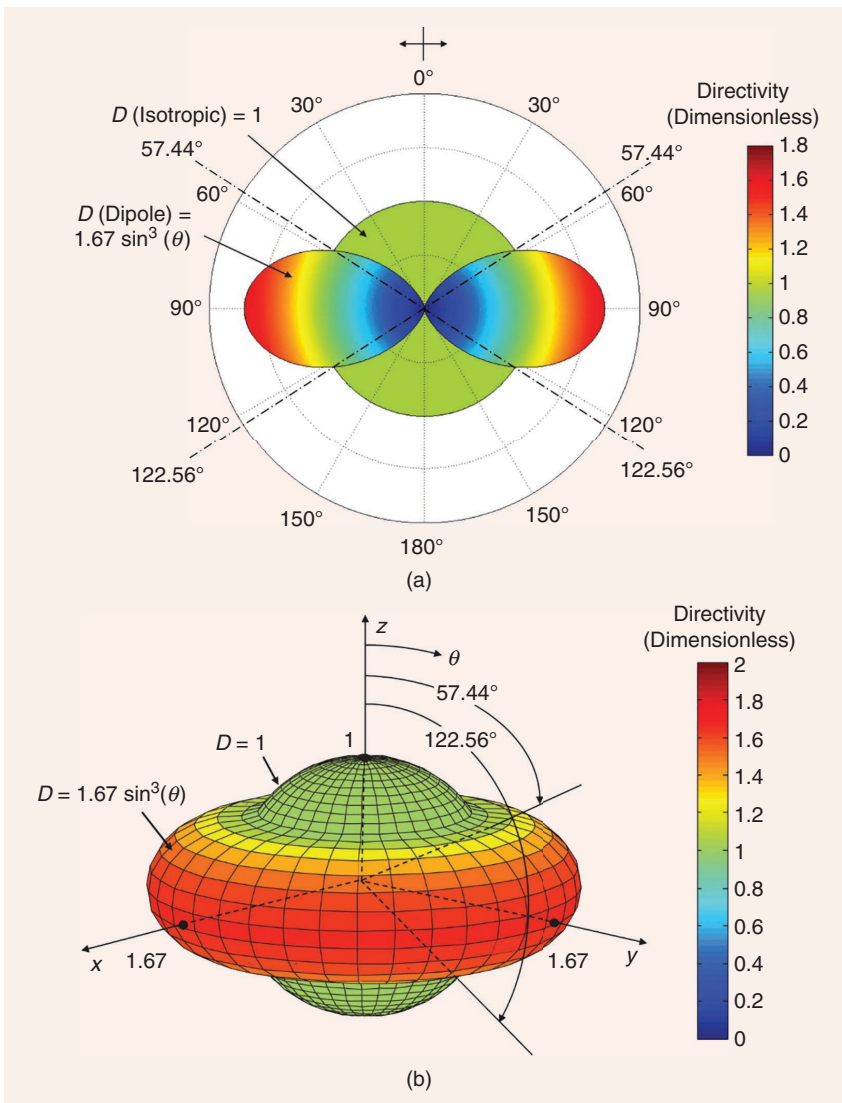


FIGURE 11. (a) 2D and (b) 3D directivity patterns of a $\lambda/2$ dipole. (Source: [2].)

introduction of an additional lobe, usually referred to as a minor lobe.

The total input impedance for an ideal dipole of overall length $l = \lambda/2$ dipole is

$$Z_{in} = 73 + j42.5. \quad (1)$$

To reduce the imaginary part of the input impedance to zero, which is usually referred to as resonating the element, the length of the dipole is reduced slightly from $\lambda/2$ until the reactance vanishes. Depending on the radius of the wire, the length l of the dipole for its first resonance is about $l = 0.47\lambda$ to 0.48λ ; the thinner the wire, the closer the length is to 0.48λ . Thus, for thicker wires, a larger segment of the wire has to be removed from $\lambda/2$ to achieve resonance.

The *directivity* of an antenna is one of the most important and fundamental parameters used to describe its radiation characteristics and performance. Stated simply, the directivity of a nonisotropic source is equal to the ratio of its radiation intensity in a given direction over that of an isotropic source. Its maximum value D_o can be expressed in mathematical form as [1]

$$D_{max} = D_o = \frac{U_{max}}{U_o} = 4\pi \frac{U_{max}}{P_{rad}}$$

where

$$\begin{aligned}
 D_{\max} &= D_o = \text{max directivity} \\
 U_{\max} &= \text{max radiation intensity} \\
 U_o &= \text{radiation intensity of isotropic radiator} \\
 P_{\text{rad}} &= \text{total radiated power.}
 \end{aligned}
 \tag{2}$$

To demonstrate the significance of the directivity, let us consider an example; in particular, let us examine the directivity of a half-wavelength dipole ($l = \lambda/2$), which can be approximated, as it provides the best fit to the exact expression [see Figure 9(b)], by [1]

$$D = D_o \sin^3 \theta = 1.67 \sin^3 \theta
 \tag{3}$$

where θ is measured from the axis along the length of the dipole, as shown in Figures 7 and 9. The values represented by this expression and those of an isotropic source ($D = 1$) are plotted, in two and three dimensions, in Figure 11(a) and (b) [1], [2]. For the 3D graphical representation of Figure 11(b), at each observation point only the largest value of the two directivities is plotted. It is apparent that when $\sin^{-1}(1/1.67)^{1/3} = 57.44^\circ < \theta < 122.56^\circ$, the dipole radiator has a greater directivity (greater intensity) in those directions than an isotropic source. Outside this range of angles, the isotropic radiator has a greater directivity (more intense radiation) than the $\lambda/2$ dipole. The maximum directivity of the dipole (relative to the isotropic radiator) occurs when $\theta = \pi/2$, and it is 1.67 (or 2.23 dB) more intense than that of the isotropic radiator of unity intensity (0 dB); both with the same radiated power.

LOOP ANTENNAS

Besides a linear dipole, another simple, inexpensive, and versatile antenna type is the loop antenna. Loop antennas take many different forms, such as a circle, rectangle, square, triangle, ellipse, and many other configurations. Because of its simplicity in analysis and construction and its symmetrical geometry, the circular loop is the most popular and has received the widest attention; its geometry is shown in Figure 12. In fact, as stated and illustrated previously in Figure 4(b), Hertz used a loop as the receiving element in his 1887 spark-gap experiment. A small loop (circular or square) is equivalent to an infinitesimal magnetic dipole whose axis is perpendicular to the plane of the loop. That is, the fields radiated by an electrically small circular or square loop have the same angular shape/pattern as an infinitesimal magnetic dipole. In the far-field region, the electric field radiated by a loop is in the horizontal ϕ direction (the E_ϕ component; thus, the loop is horizontally polarized).

Loop antennas are usually classified into two categories: electrically small and electrically large. Electrically small antennas are those whose overall length (circumference) is usually less than about one tenth of a wavelength

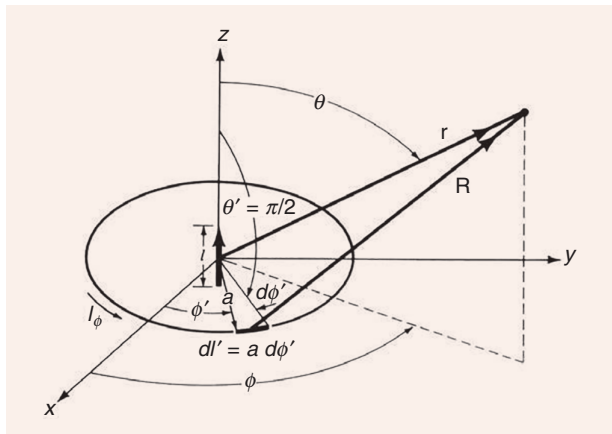


FIGURE 12. The geometry of a circular loop of radius a . (Source: [1].)

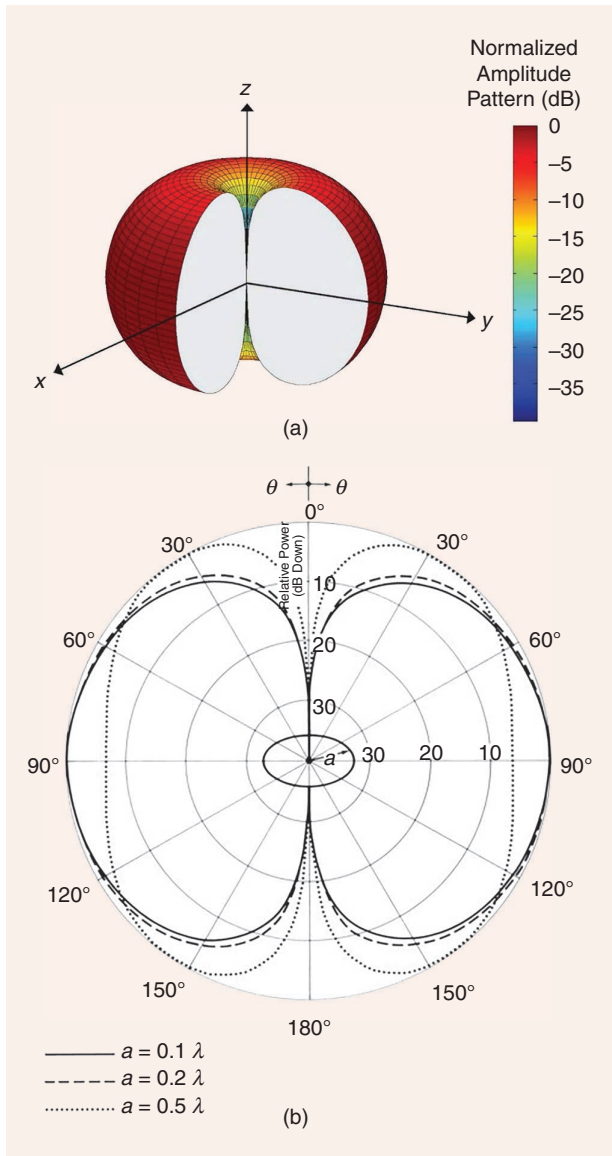


FIGURE 13. (a) 3D and (b) 2D normalized amplitude patterns of a circular loop. (Source: [1].)

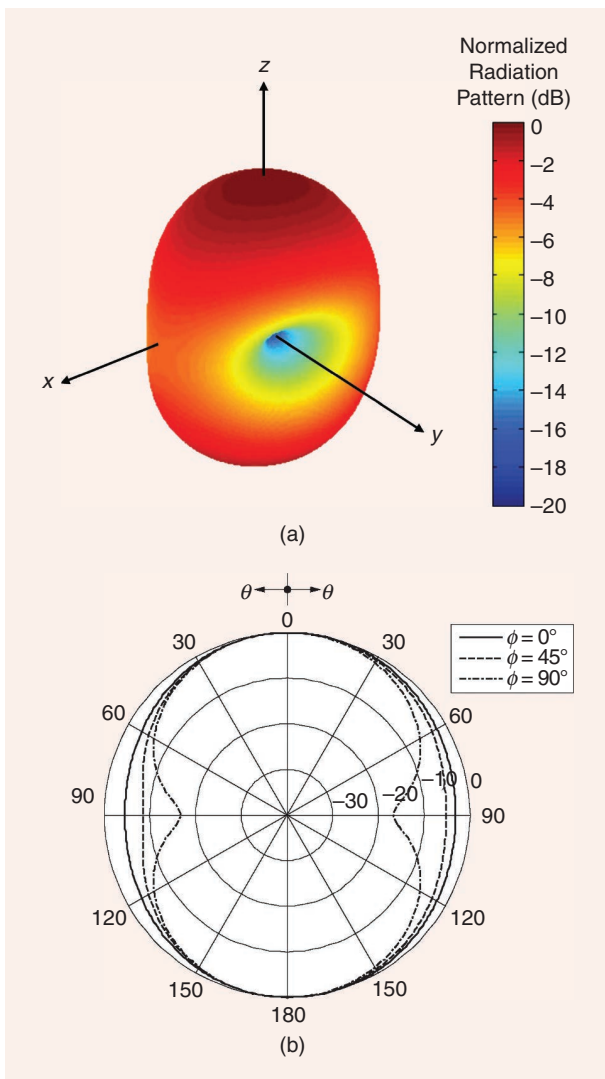


FIGURE 14. (a) 3D and (b) 2D (elevation) normalized amplitude patterns of a circular loop of circumference $C = \lambda$. (Source: [1].)

($C < \lambda/10$). However, electrically large loops are those whose circumference is about one free-space wavelength ($C \sim \lambda$). Most of the applications of loop antennas are in the high-frequency (HF; 3–30-MHz), very-high-frequency (30–300-MHz), and UHF (300–3,000-MHz) bands. When used as field probes, they find applications even in the microwave frequency range.

Loop antennas with electrically small circumferences or perimeters have small radiation resistances, which are usually smaller than their loss resistances. Because of this characteristic, small loops are very poor radiators, and they are seldom employed for transmission in radio communication. However, when they are used in any such application, it is usually in the receiving mode, such as in portable radios and pagers, where the antenna efficiency is not as important as the signal-to-noise ratio. Small loops are also used as probes for field measurements and as directional antennas for radio wave navigation. The field amplitude pattern and distribution

of electrically small antennas of any shape (circular, square, rectangular, elliptical, or any other configuration; as long it is small) are similar to those of an infinitesimal dipole with a null perpendicular to the plane of the loop and with its maximum along the plane of the loop, referred to as a broadside radiator, as illustrated in Figure 13(a) for a circular loop of radius $a = 0.1\lambda$. It is apparent that, for the 0.1λ circumference loop, its pattern is basically that of a figure eight ($\sin \theta$). Assuming a uniform current distribution, the 2D patterns for radii of $a = 0.1\lambda$, 0.2λ , and 0.5λ are displayed in Figure 13(b). Note that, for the $a = 0.5\lambda$ radius pattern, even assuming a uniform current distribution, which is not valid for such a large radius, the maximum has moved toward the $\theta = 0^\circ$ direction.

It has been shown [58] and is illustrated in Figure 14 that, when the circumference of the loop is about one wavelength ($C \approx \lambda$), its maximum radiation based on a non-uniform current distribution is along its axis ($\theta = 0^\circ, 180^\circ$), which is perpendicular to the plane of the loop. Under this one-wavelength circumference, the loop with this feature is referred to as an *endfire radiator*. The endfire radiation characteristic of the near one-wavelength circumference ($C \approx \lambda$) loop antenna was utilized to design Yagi-Uda arrays, whose basic elements (feed, directors, and reflectors) are circular loops [59], [60], [61], [62]. Because of its many applications, the one-wavelength circumference circular loop antenna is considered as fundamental as the half-wavelength dipole.

The radiation resistance of the loop can be increased, and made comparable to the characteristic impedance of practical transmission lines, by increasing (electrically) its perimeter and/or the number of turns. Another way to increase the radiation resistance of the loop is to insert, within its perimeter or circumference, a ferrite core of very high permeability; doing this will raise the magnetic field intensity and hence the radiation resistance. This forms what is called the *ferrite loop*.

Electrically large loops, with near one-wavelength circumference ($C \approx \lambda$), are fundamental and are used primarily in directional arrays, such as in Yagi-Uda arrays and helical antennas.

CONCLUSIONS

In addition to the dipole and loop of this article, the evolution of other classical antenna types, single elements and arrays, are discussed in a series of articles that will follow in future issues of *IEEE Antennas and Propagation Magazine*.

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