Chapter

Introductory Chapter: Novel Radio Frequency Antennas

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1. Introduction

Antennas are part of radio and television broadcasting, point-to-point radio communication systems, wireless LAN, cell phones, radar, medical systems, and spacecraft communication. Low-profile compact antennas are crucial in the development of wireless communication and wearable biomedical systems. Compact, low-profile, and light-weight printed antennas are the best solution for communication, IoT, and medical systems. Printed antennas' low production costs are crucial in development of low-cost communication systems. Moreover, the advantage of an integrated compact low-cost feed network is attained by integrating the antenna feed network with the antennas on the same printed board. Wireless communication and medical industry are in continuous growth in the last few years. Printed antennas are used in communication systems that employ MIC, MEMS, LTCC, and MMIC technologies.

2. Introduction to RF antennas

Antennas are major components in communication systems [1–19]. Mobile antenna systems are presented in [11]. Transmitting antennas efficiently radiate electromagnetic fields and match RF systems to space. Antennas may transmit or receive electromagnetic fields. Transmitting antennas convert electric current to electromagnetic fields. Receiving antennas convert electromagnetic fields to electric current. In transmitting antennas, an alternating current is created in the elements by applying a voltage at the antenna feed network, causing the antenna to radiate an electromagnetic energy. In receiving mode, an electromagnetic field from an outer source induces an alternating current in the receiving antenna and generates a voltage at the antenna's feed network. Antennas are used in outdoor and indoor communication systems. Antennas can be used in under water communication systems. Antennas may be implanted inside human body and operate as wearable sensors. Receiving antennas such as parabolic and horn antennas incorporate shaped reflective surfaces to receive the electromagnetic fields and focus the fields to the conductive receiving elements.

The book consists of four sections presenting several types of novel antennas.

Section 1: Introduction

Section 2: Novel Antennas for 5G, IoT, and Medical Applications

Section 3: Novel RF Antennas Technologies

Section 4: Advanced Antenna Arrays

The design and electrical performance of several novel antennas are presented in this book.

3. Type of antennas

Small antennas for communication systems.

Monopole—quarter wavelength wire antenna.

Dipole—Dipole antenna consists of two quarter wavelength wires. Dipole is a half wavelength wire antenna. The monopole and dipole antennas couple to the electric field of the electromagnetic wave in the region near the antenna.

Slot antenna—half wavelength slot: A *slot antenna* consists of a metal surface with a *slot* cut out.

Biconical antennas—biconical half wavelength wire antenna: Biconical antenna is a wideband antenna made of two conical conductive objects.

Loop antennas—Loop antenna is known as a magnetic loop. The loop antenna behaves as an inductor. The loop antenna couples the electromagnetic magnetic field in the region near the loop antenna. Monopole and dipole antennas couple to the electric field.

Helical antennas—helical wire antennas.

Printed antennas—antennas printed on a dielectric substrate.

Aperture antennas for base station communication systems

- Horn and open waveguide
- Reflector antennas
- Antenna arrays
- Microstrip and printed antenna arrays
- Slot antenna arrays

A comparison of directivity and gain values for several antennas is given in **Table 1**.

Phased arrays: Phased array antennas are electrically steerable. The physical antenna can be stationary. Phased arrays, smart antennas, incorporate active components for beam steering.

Antenna type	Directivity (dBi)	Gain (dBi)
Isotropic radiator	0	0
Dipole $\lambda/2$	2	2
Dipole above ground plane	6–4	6–4
Microstrip antenna	7–8	6–7
Yagi antenna	6–18	5–16
Helix antenna	7–20	6–18
Horn antenna	10–30	9–29
Reflector antenna	15–60	14–58

Table 1.
Antenna directivity versus antenna gain.

3.1 Steerable antennas

- Arrays with switch-able elements. The array may be partially electronically and mechanically steerable arrays.

- Hybrid antenna systems—for fully electronically steerable arrays. The design can be based on digital beam forming (DBF). These systems may consist of phase and amplitude shifters for each radiating element.

- In digital beam forming, the steering is performed directly in a digital level. DBF allows the most powerful and flexible control of the antenna beam steering.

4. Monopole antenna for communication systems

Monopole antenna is usually a one-quarter wavelength-long conductor mounted above a ground plane or the earth as shown in **Figure 1**. Based on the image theory behind the ground plane, the monopole image is located. The monopole antenna and the monopole image form a dipole antenna. Monopole antenna is half a dipole that radiates electromagnetic fields above the ground plane. The impedance of 0.5 λ monopole antenna is around 37 Ω. The beam width of a monopole, 0.25 λ long, is around 40°. The directivity of a monopole, 0.25 λ long, is around 3 dBi to 5dBi. Usually in wireless communication systems, very short monopole antenna is employed. The impedance of 0.05 λ monopole antenna is around 1 Ω with capacitive reactance. The beam width of a monopole, 0.05 λ long, is around 45°. The directivity of a monopole, 0.05 λ long, is around 3 dBi.

Inverted monopole antenna is shown in **Figure 2a**. Loaded monopole antenna is shown in **Figure 2b**. Monopole antennas may be printed on a dielectric substrate as part of wearable communication devices.

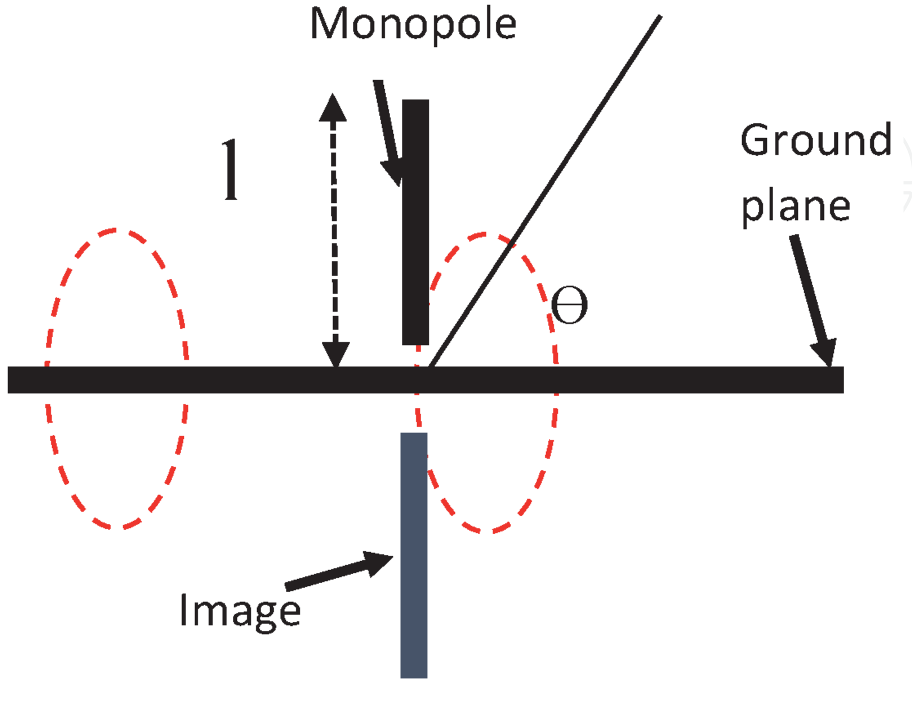

Figure 1.
Monopole antenna.

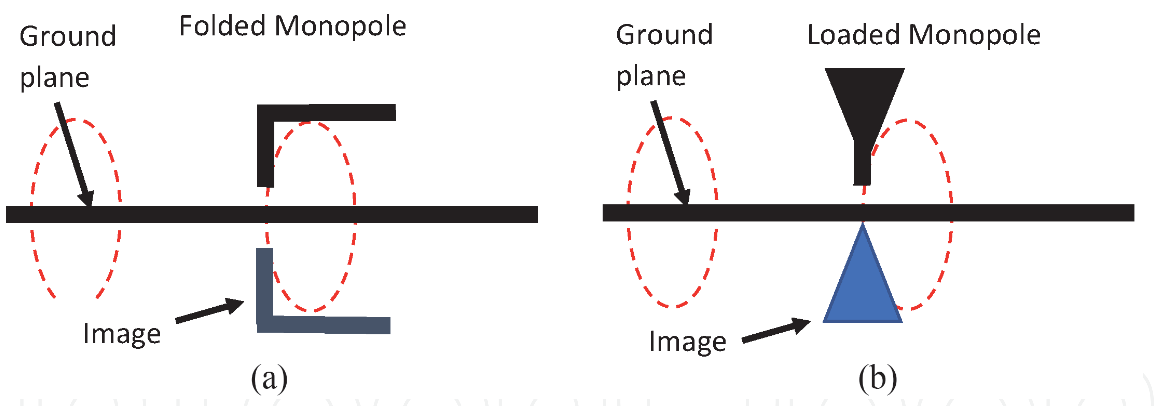

Figure 2.
(a) Inverted monopole antenna. (b) Loaded monopole antenna.

5. Evaluation of basic antenna parameters

Monopole and dipole antennas are the most basic antennas. Evaluation of the electrical parameters of dipole antenna is used to define basic antenna parameters such as radiation pattern, directivity, and antenna impedance. Dipole antenna is a small wire antenna. It consists of two conductors excited by a voltage fed via a transmission line as presented in **Figure 3**. The center conductor of the transmission line is connected to one of the conductors and the outer conductor is connected to the second conductor. The half-wave dipole consists of two conductors, in which each conductor is approximately quarter wavelength long. We can compute the electromagnetic fields radiated from the dipole by defining a potential function, Eq. (1).

5.1 Dipole antenna

The electric potential function is φ_l. The magnetic potential function is A. The potential function is given in Eq. (1).

$$\begin{aligned} \varphi_l &= \frac{1}{4\pi\varepsilon_0} \int_c \frac{\rho_l e^{\,j(\omega t - \beta R)}}{R} \mathrm{dl} \\ A_l &= \frac{\mu_0}{4\pi} \int_c \frac{\mathrm{ie}^{\,j(\omega t - \beta R)}}{R} \mathrm{dl} \end{aligned} \tag{1}$$

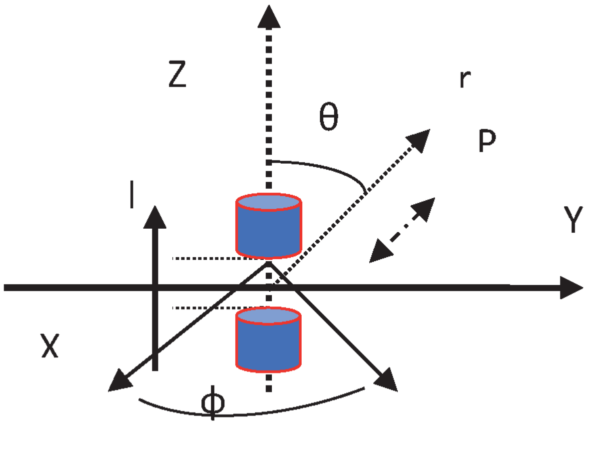

Figure 3.
Dipole antenna.

5.2 Radiation from small dipole

The length of a small dipole is small compared to its wavelength and is called elementary dipole. The current along a small dipole is uniform. We can compute the electromagnetic fields radiated from the dipole in spherical coordinates by using the potential function given in Eq. (1). The electromagnetic field at a point P(r, θ, φ) is listed in Eq. (3). The electromagnetic fields in Eq. (3) vary as $\frac{1}{r}$, $\frac{1}{r^2}$, $\frac{1}{r^3}$. For r << 1, the dominant component of the field varies as $\frac{1}{(r)^3}$ and is written in Eq. (4). These fields are the dipole near fields. In the near field, the waves are standing waves and the energy oscillates in the antenna near zone and is not radiated to the free space. The real part of the pointing vector equals to zero. At r >> 1, the dominant component of the field varies as 1/r as written in Eq. (5). These fields are the dipole far fields. In the far fields, the electromagnetic fields vary as $\frac{1}{r}$ and sinθ. Wave impedance in free space is given in Eq. (6).

6. Dipole radiation pattern

The antenna radiation pattern represents the radiated fields in space at a point P (r, θ, φ) as a function of θ and φ. The antenna radiation pattern is three dimensional. When φ is constant and θ varies, we get the E plane radiation pattern. When φ varies and θ is constant, usually θ = π/2, we get the H plane radiation pattern.

6.1 Dipole E plane radiation pattern

The dipole E plane radiation pattern is given in Eq. (2) and presented in **Figure 4**.

$$|E_\theta| = \eta_0 \frac{l\beta I_0 |\sin\theta|}{4\pi r} \tag{2}$$

At a given point P(r, θ, φ), the dipole E plane radiation pattern is given in Eq. (7).

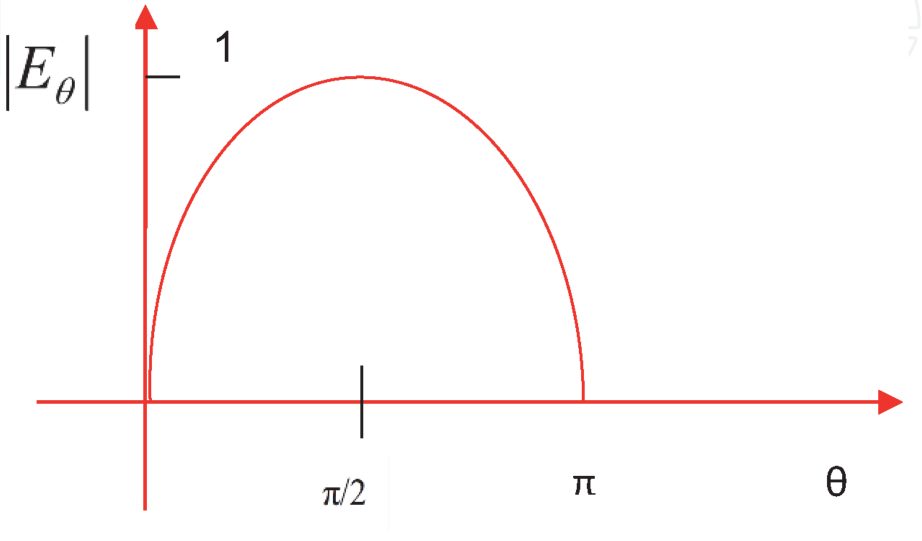

Figure 4.
Dipole E plane radiation pattern.

$$
\begin{aligned}
E_r &= \eta_0 \frac{\mathrm{lI}_0 \cos\theta}{2\pi r^2}\left(1-\frac{j}{\beta r}\right)e^{\,j(\omega t-\beta r)} \\
E_\theta &= j\eta_0 \frac{\beta \mathrm{lI}_0 \sin\theta}{4\pi r}\left(1-\frac{j}{\beta r}-\frac{1}{(\beta r)^2}\right)e^{\,j(\omega t-\beta r)} \\
H_\varphi &= j\frac{\beta \mathrm{lI}_0 \sin\theta}{4\pi r}\left(1-\frac{j}{\beta r}\right)e^{\,j(\omega t-\beta r)} \\
H_r &= 0 \quad H_\theta = 0 \quad E_\phi = 0
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
I &= I_0 \cos\omega t \\
E_r &= -j\eta_0 \frac{\mathrm{lI}_0 \cos\theta}{2\pi\beta r^3} e^{\,j(\omega t-\beta r)} \\
E_\theta &= -j\eta_0 \frac{\mathrm{lI}_0 \sin\theta}{4\pi\beta r^3} e^{\,j(\omega t-\beta r)} \\
H_\varphi &= \frac{\mathrm{lI}_0 \sin\theta}{4\pi r^2} e^{\,j(\omega t-\beta r)}
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
E_r &= 0 \\
E_\theta &= j\eta_0 \frac{l\beta I_0 \sin\theta}{4\pi r} e^{\,j(\omega t-\beta r)} \\
H_\varphi &= j\frac{l\beta I_0 \sin\theta}{4\pi r} e^{\,j(\omega t-\beta r)}
\end{aligned} \tag{5}
$$

$$
\frac{E_\theta}{H_\varphi} = \eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \tag{6}
$$

$$
\begin{aligned}
|E_\theta| &= \eta_0 \frac{l\beta I_0 |\sin\theta|}{4\pi r} = A|\sin\theta| \\
&\text{Choose} \quad A = 1 \\
|E_\theta| &= |\sin\theta|
\end{aligned} \tag{7}
$$

Dipole E plane radiation pattern in spherical coordinate system is shown in **Figure 5**.

6.2 Dipole H plane radiation pattern

For θ = π/2, the dipole H plane radiation pattern is given in Eq. (8) and presented in **Figure 6**.

$$
|E_\theta| = \eta_0 \frac{l\beta I_0}{4\pi r} \tag{8}
$$

The dipole H plane radiation pattern in xy plane is a circle with r = 1. At a given point P(r, θ, φ), the dipole H plane radiation pattern is given in Eq. (9). The radiation pattern of a vertical dipole is omnidirectional. It radiates equal power in all azimuthal directions perpendicular to the axis of the antenna.

6.3 Antenna radiation pattern

An antenna radiation pattern is shown in **Figure 7**. The antenna main beam is defined between the points that the maximum relative field level E decays to

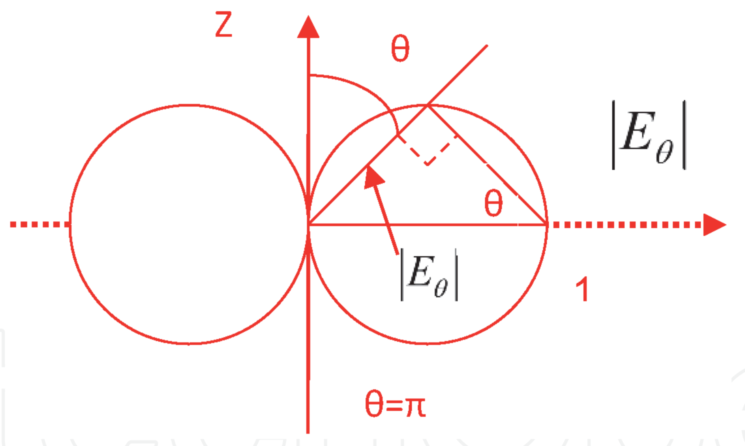

Figure 5.
Dipole E plane radiation pattern in spherical coordinate system.

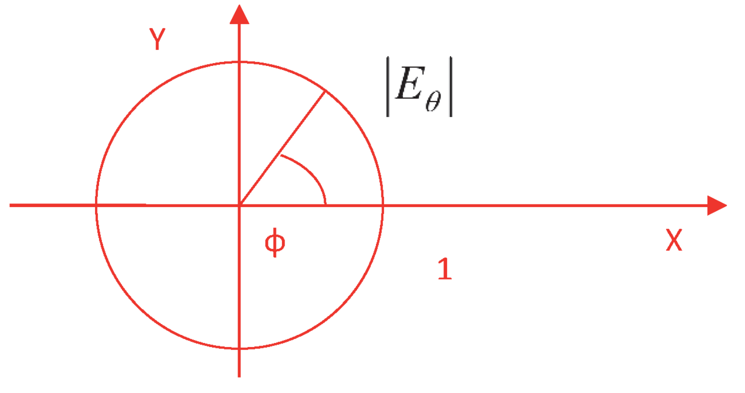

Figure 6.
Dipole H plane radiation pattern for θ = π/2.

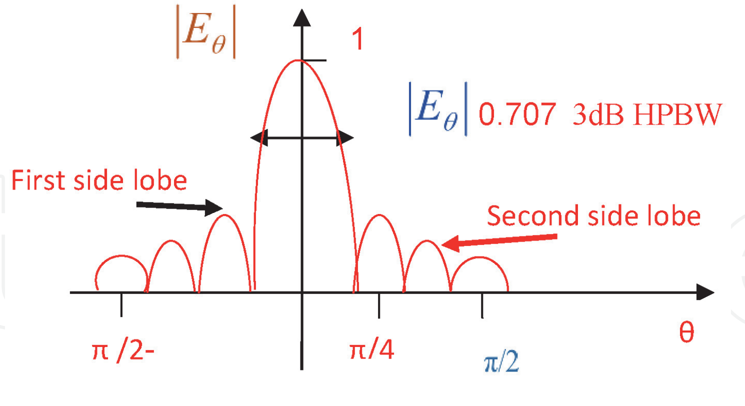

Figure 7.
Antenna typical radiation pattern.

0.707E. Half of the radiated power, −3 dB points, is concentrated in the antenna main beam. The antenna main beam is defined as the 3 dB beam width. Radiation to undesired direction is concentrated. The antenna side lobes present radiation to undesired direction.

$$|E_\theta| = \eta_0 \frac{l\beta I_0|\sin\theta|}{4\pi r} = A$$
$$\text{Choose} \quad A = 1 \tag{9}$$
$$|E_\theta| = 1$$

For a dipole, the power intensity varies as $\left(\sin^2\theta\right)$. At θ = 45° and θ = 135° the radiated power equals to half the power radiated toward θ = 90°. The dipole beam width is θ = (135–45) =90°.

7. Dipole directivity

Directivity is defined as the ratio between the amounts of energy propagating in a certain direction compared to the average energy radiated to all directions over a sphere as written in Eqs. (10) and (11).

$$D = \frac{P(,)maximal}{P(,)average} = 4\frac{P(,)maximal}{Prad} \quad (10)$$

$$P(,)average = \frac{1}{4}P(,)sindd = \frac{Prad}{4} \quad (11)$$

The radiated power from a dipole is calculated by computing the pointing vector P as given in Eq. (12).

$$\begin{gathered} P = 0.5(E \times H) = \frac{15\pi I_0^2 l^2 \sin^2\theta}{r^2\lambda^2} \\ W_T = \int_s P \cdot \mathrm{ds} = \frac{15\pi I_0^2 l^2}{\lambda^2}\int_0^\pi \sin^3\theta d\theta \int_0^{2\pi} d\varphi = \frac{40\pi^2 I_0^2 l^2}{\lambda^2} \Big) \end{gathered} \quad (12)$$

The overall radiated energy is WT. WT is computed as written in Eq. (12), by integration of P over an imaginary sphere surrounding the dipole. The power flow of an isotropic element equal to the overall radiated energy divided by the area of the sphere, $4\pi r^2$, see Eq. (13). The dipole directivity at θ = 90° is 1.5 as given in Eq. (14). For small antennas or for antennas without losses, D = G, losses are negligible. For a given θ and φ for small antennas, the approximate directivity is given by Eq. (15).

$$\begin{gathered} \oint_s \mathrm{ds} = r^2 \int_0^\pi \sin\theta d\theta \int_0^{2\pi} d\phi = 4\pi r^2 \\ P_{\mathrm{iso}} = \frac{W_T}{4\pi r^2} = \frac{10\pi I_0^2 l^2}{r^2\lambda^2} \end{gathered} \quad (13)$$

$$\begin{gathered} D = \frac{P}{P_{\mathrm{iso}}} = 1.5\sin^2\theta \\ G_{\mathrm{dB}} = 10\log_{10} G = 10\log_{10} 1.5 = 1.76\mathrm{dB} \end{gathered} \quad (14)$$

$$\begin{gathered} D = \frac{41253}{\theta_{3\mathrm{dB}}\phi_{3\mathrm{dB}}} \\ G = \xi D \quad \xi = \mathrm{Efficency} \end{gathered} \quad (15)$$

Antenna losses degrade the antenna efficiency. Antenna losses consist of conductor loss, dielectric loss, radiation loss, and mismatch losses. For resonant small antennas, ξ =1. For reflector and horn antennas, the efficiency varies between $\xi = 0.5$ and.

$\xi = 0.7$. The beam width of a small dipole, 0.1 λ long, is around 90°. The 0.1 λ dipole impedance is around 2 Ω. The beam width of a dipole, 0.5 λ long, is around 80°. The impedance of 0.5 λ dipole is around 73 Ω.

8. Antenna impedance

Antenna impedance determines the efficiency of transmitting and receiving energy in antennas. The dipole impedance is given in Eq. (16).

$$R_{rad} = \frac{2W_T}{I_0^2}$$
$$For\ a\ Dipole:\ R_{rad} = \frac{80\pi^2 l^2}{\lambda^2} \tag{16}$$

8.1 Loop antennas for wireless communication systems

Loop antennas are compact, low-profile, and low-cost antennas. Loop antennas are employed in wearable wireless communication systems. The loop antenna is referred to as the dual of the dipole antenna, see **Figure 8**. A small dipole has magnetic current flowing (as opposed to electric current as in a regular dipole), the loop antenna fields are similar to that of a small loop. The short dipole has a

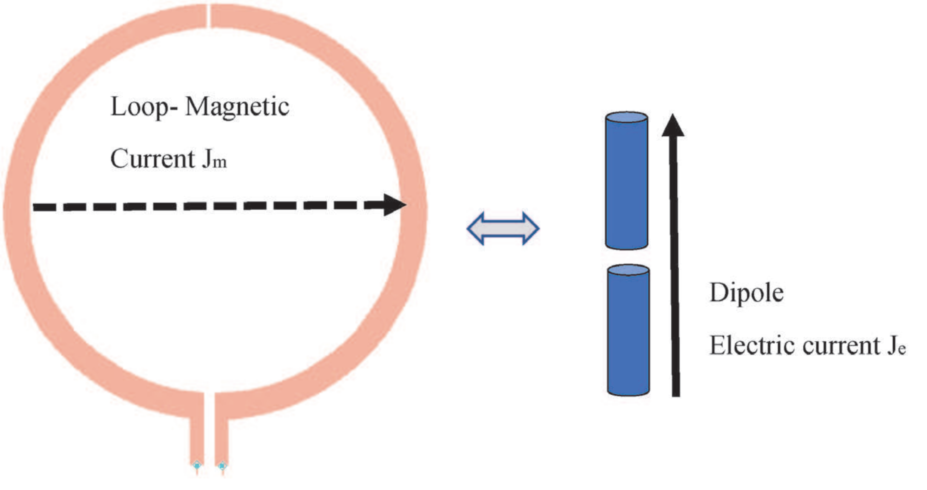

Figure 8.
Duality relationship between dipole and loop antennas.

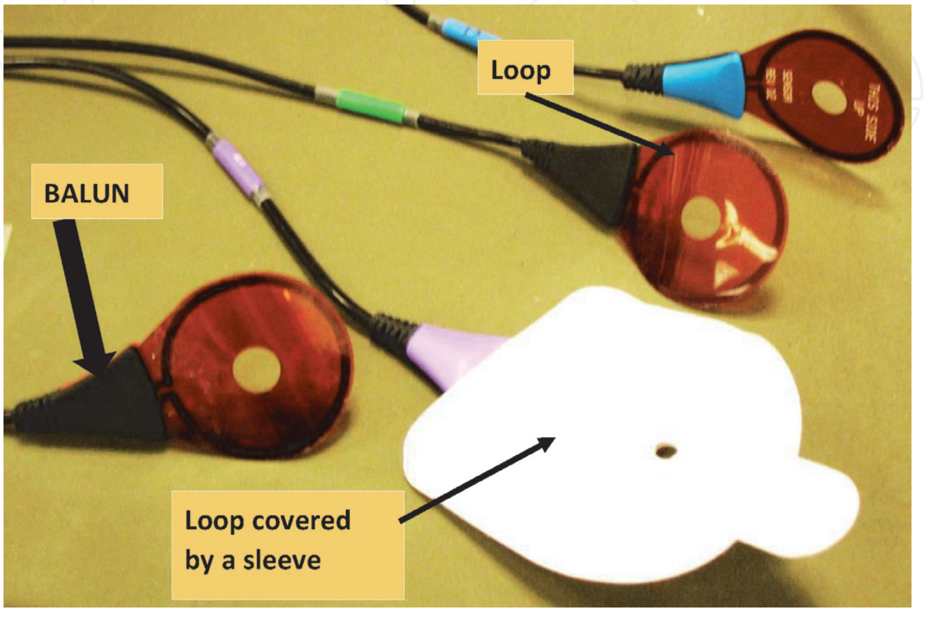

Figure 9.
Photo of loop antennas.

capacitive impedance and the impedance of a small loop is inductive. A photo of loop antennas is shown in **Figure 9**.

8.2 Printed antennas

Printed antennas have been analyzed and presented in several papers and books in the last 30 years [1–18]. Microstrip antennas are the most popular type of compact printed antennas. Printed Slot, PIFA, and dipole antennas are employed in several wireless communication systems. Printed antennas are used in wireless communication systems, wearable devices, IoT applications, novel 5G communication links, seekers, and medical systems.

Printed antennas possess attractive features such as light weight, compactness, flexibility, and are cheap compared to other similar antennas.

8.3 Applications of wearable antennas

- Medical
- Wireless communication
- WLAN
- GPS
- Military applications

9. Microstrip antennas

Microstrip antennas are printed on a on a dielectric substrate with low dielectric losses. Cross section of the microstriop antenna is shown in **Figure 10**.

Microstrip antennas are thin patches etched on a dielectric substrate εr. The substrate thickness, H, is less than 0.1λ. Microstrip antennas are widely presented in [1–18].

Advantages of microstrip antennas:

- Flexible
- Low-profile compact uniform arrays
- Compact
- Low-cost antennas

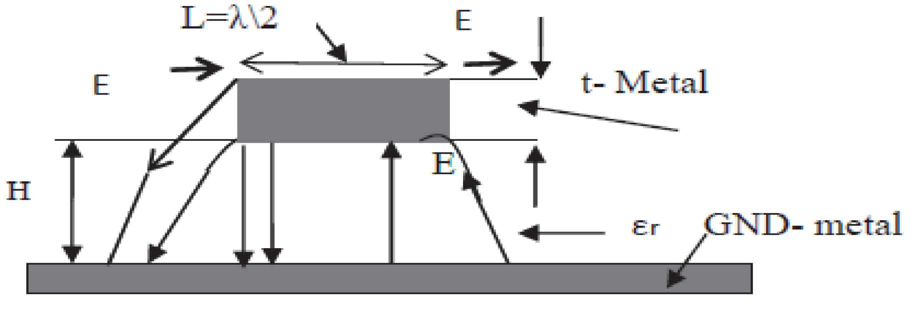

Figure 10.
Microstrip antenna cross section.

Disadvantages of microstrip antennas:

- Narrow bandwidth (usually 0.5–5%). However, wider bandwidth may be achieved by using multilayer structure and novel technologies.
- Limited power handling up to 50 W.
- High feed network losses at high frequencies.

The electric field along the radiating edges is presented in **Figure 11**. The magnetic field is perpendicular to the electric field according to Maxwell's equations. At the edge of the strip (X/L = 0 and X/L = 1), the magnetic field drops to zero, because there is no conductor to carry the electromagnetic current, it is maximum in the patch center. The electric field is at maximum level (with opposite polarity) at the patch edges (X/L = 0 and X/L = 1) and zero at the patch center. The ratio of electric to the magnetic field is proportional to the impedance that we measure when we feed the patch. Microstrip antennas may be fed by a microstrip line or by a coaxial line or probe feed. By varying the location of the antenna feed point between the patch center and the patch edge, we can get a 50 Ω impedance or any other desired impedance. Microstrip antenna may have any arbitrary shape such as square, triangle, circle, ring, rectangular, and fractal shape as presented in **Figure 12**.

The antenna dimension W is given by Eq. (17). The antenna bandwidth is given in Eq. (18).

$$W = \frac{c}{2f\sqrt{\epsilon_{eff}}} \tag{17}$$

$$BW = \frac{H}{\sqrt{\epsilon_{eff}}} \tag{18}$$

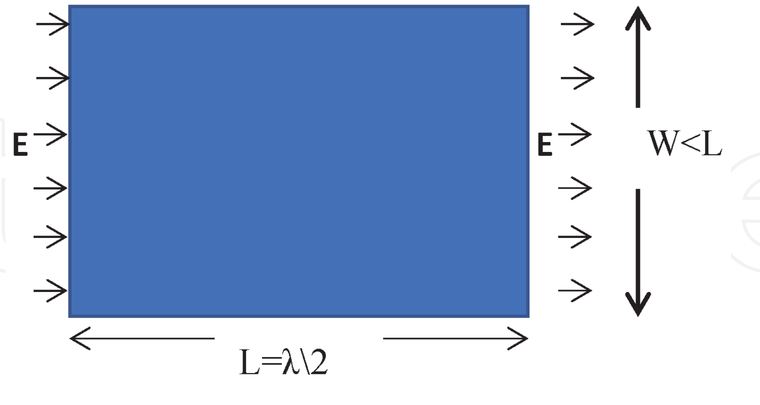

Figure 11.
Rectangular microstrip antenna.

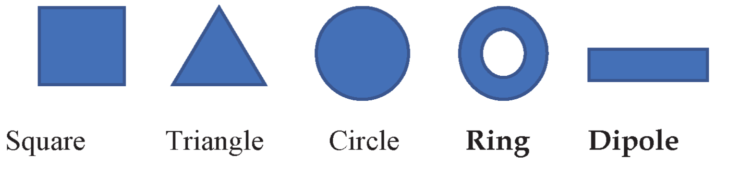

Figure 12.
Microstrip antenna shapes.

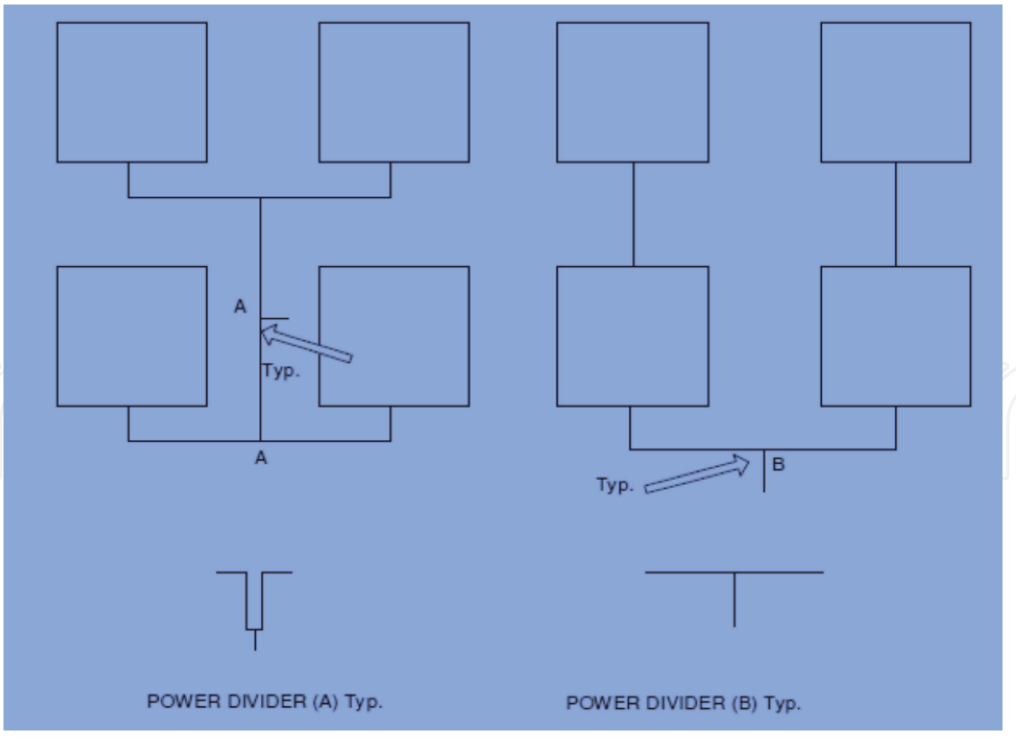

Figure 13.
MM wave microstrip antenna array. (a) Parallel array feed network. (b) Parallel-series array feed network.

The gain of microstrip patch is between 0 and 5 dBi. The microstrip patch gain is a function of the antenna configuration, structure, and dimensions. Microstrip antenna arrays are used to get gain up to 30 dB. In microstrip patch arrays, a low-profile and low-cost feed and matching network is attained by integrating the antenna feed network with the radiating patches on the same substrate. Microstrip antenna feed networks are shown in **Figure 13**. A parallel feed network is shown in **Figure 13a**. A parallel–series feed network is shown in **Figure 13b**.

10. Conclusions

This chapter presents electrical parameters of several basic antennas. Antennas are part of radio and television broadcasting, point-to-point radio communication systems, wireless LAN, cell phones, radar, medical systems, and spacecraft communication. Compact wideband efficient antennas are crucial in communication systems.

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