

2006-01-01

## Planar Antennas

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### Recommended Citation

Cheng, Z. et al. (2006) Planar antennas. *IEEE Microwave Magazine*, 2006, Vol.7, no. 1, pp.63-73.  
doi:10.1109/MW-M.2006.250315

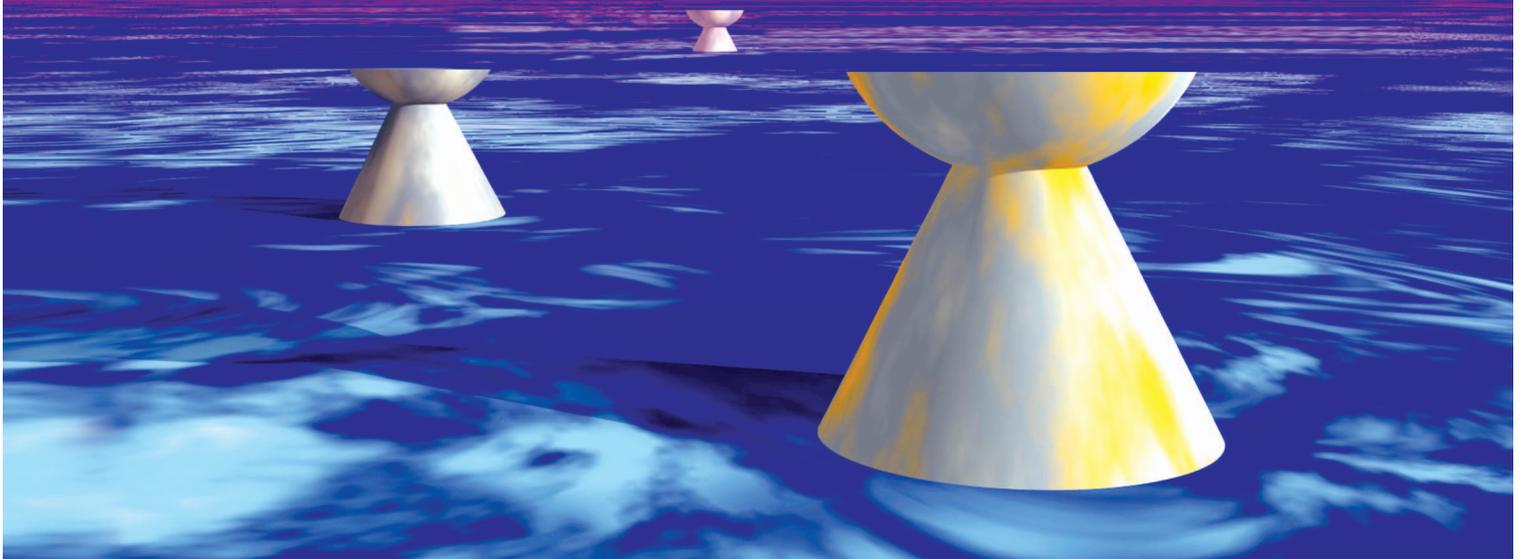
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**T**he release of an extremely wide spectrum of 3.1–10.6 GHz for commercial applications has greatly spurred the research and development of microwave ultrawideband (UWB) technology for communications, imaging, radar, and localization applications. In accordance, many techniques to broaden the impedance bandwidth of small antennas and to optimize the characteristics of the broadband antennas have been widely investigated. This article reviews the state of the art in broadband antennas for emerging UWB applications and addresses the important issues of the broadband antenna design for UWB applications. First, a variety of planar monopoles with finite ground planes are reviewed. Next, the roll antennas with enhanced radia-

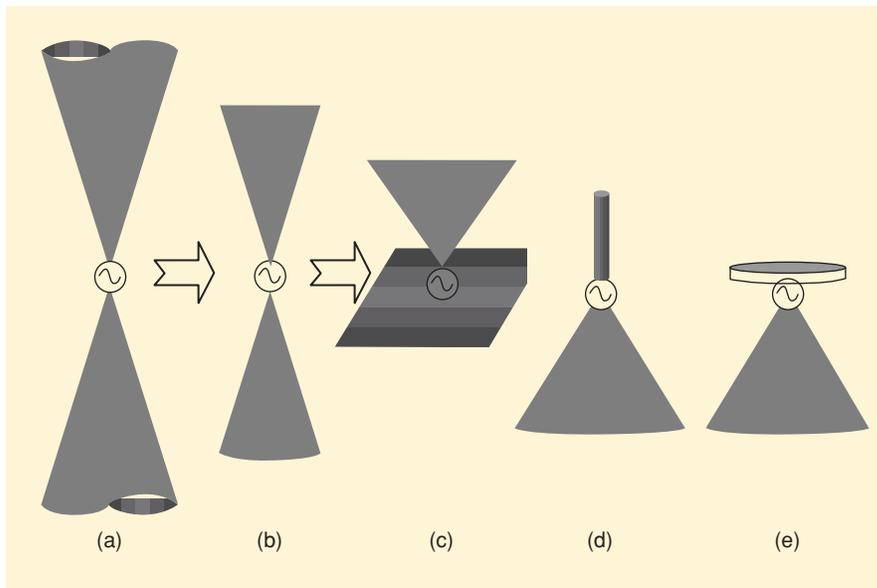
tion performance are outlined. After that, the planar antennas printed on PCBs are described. A directional antipodal Vivaldi antenna is also presented for UWB applications. Last, a UWB antenna for wearable applications is exemplified.

## Introduction

UWB systems are based on transmitting and receiving impulses with extremely wide spectra. Recently, extremely broad frequency ranges have been allocated for UWB imaging, communications, and radar and localization systems. For example, the Federal Communication Commission (FCC) legalizes a 10-dB bandwidth of 7.5 GHz (3.1–10.6 GHz) with a limited emission level (lower than  $-41.3$  dBm/MHz) for

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**Figure 1.** The evolution of conical antennas.



**Figure 2.** The disccone antenna developed at I<sup>2</sup>R.

emerging commercial microwave UWB applications [1]. Accordingly, the demands of broadband antennas have been increased greatly. In general, the antennas for UWB systems should have sufficiently broad operating bandwidths for impedance matching and high-gain radiation in desired directions. For example, transverse electric magnetic (TEM) horns feature very broad well-matched bandwidths and have been widely studied and applied [2]–[6]. Theoretically, frequency-independent antennas, which have a constant performance at all frequencies, can also be applied to broadband design. A typical design is the self-complementary log-periodic structures, such as planar log-periodic slot antennas, bidirectional log-periodic antennas, log-periodic dipole arrays, two/four-arm log spiral antennas, and conical log-spiral antennas [7]. However, for the

log-periodic antennas, frequency-dependant changes in their phase centers severely distort the waveforms of radiated pulses [8]. Biconical antennas are the earliest antennas used in wireless systems constructed by Sir Oliver Lodge in 1897, as mentioned by John D. Kraus [9]. They featured relatively stable phase centers with broad well-matched bandwidths due to the excitation of TEM modes. Following that, many diverse variations of biconical antennas such as finite biconical antennas, disccone antennas, and single-cone with resistive loadings are formed and

optimized for broad impedance bandwidths [10]–[12]. The cylindrical antennas with resistive loading also feature broadband impedance characteristics [13]–[15]. However, the antennas mentioned above are seldom used in portable devices due to their bulky size or directional radiation—although they are widely used in electromagnetic measurements. Alternatively, planar monopoles (dipoles) or disc antennas have been proposed because of their broad bandwidths and small size [16]–[19]. The earliest planar dipole may be the Brown-Woodward bowtie antenna, which is a simple and planar version of a conical antenna [9], [20]. The planar antennas for broadband and multiband applications were reviewed in [21].

On the other hand, there are special design considerations for antennas for the UWB systems, especially for microwave wireless communications [22]. Studies have shown that the antenna designs should be considered from a systems point of view, and the system transfer function is a good measure to evaluate the performance of the antennas in terms of system gain (the magnitude of the system transfer function) and group delay (the derivative of phase of the system transfer function), especially for the impulsive systems. The requirements for UWB antennas can vary for different schemes, namely a multiband orthogonal frequency division multiplexing (OFDM) scheme—in which the available UWB band is divided into several subbands and employs signals with single or multicarrier—and the single band impulsive scheme, where one or a few impulses with single carrier or without any carrier occupy the whole UWB band. Due to the unique system characteristics, the requirements for the antenna design are different. For example, in the multiband scheme, the consistent or flat gain response of the UWB antennas is more important than a constant group delay or a linear

phase response, which is conversely more important in the single band scheme. Therefore, the performance of UWB antennas can be assessed in terms of the system transfer function and group delay together with conventional frequency-domain parameters such as return loss, gain, radiation patterns, and polarization matching path loss as well as the time-domain parameters such as pulse waveforms, and fidelity.

In this article, the state of the art in broadband antennas for emerging UWB applications is reviewed, and the important issues related to the broadband antenna design for UWB applications are highlighted. In particular, a variety of planar monopoles with finite ground planes are introduced. The roll antennas for enhanced radiation performance are outlined. The small planar antennas printed on PCBs are described. A directional antipodal Vivaldi antenna is also presented. The wearable UWB antenna on a human head is investigated as a case study.

### Planar Monopoles

It is well known that the infinite biconical antennas can be considered as an infinite uniform transmission line, which can radiate a dominant TEM mode as shown in Figure 1(a). Thus, this structure features a frequency-independent impedance response. However, in engineering, a finite biconical antenna and single cone with a ground plane are of more practical interest, as shown in Figure 1(b) and (c); they are analogous to a terminated transmission line with frequency-dependent reflection at its ends. Therefore, the structures have a limited well-matched impedance bandwidth but a stable phase center within the bandwidth. The conical

antennas are usually fed by coaxial lines. The biconical antennas can be asymmetrical with the cones of different geometries. For example, the upper cone can be a stem, a  $0^\circ$  finite cone [Figure 1(d)] or disc, a  $90^\circ$  finite cone [Figure 1(e)]. The discone antennas have been widely applied in UWB systems, particularly for channel measurements and system testing [23].

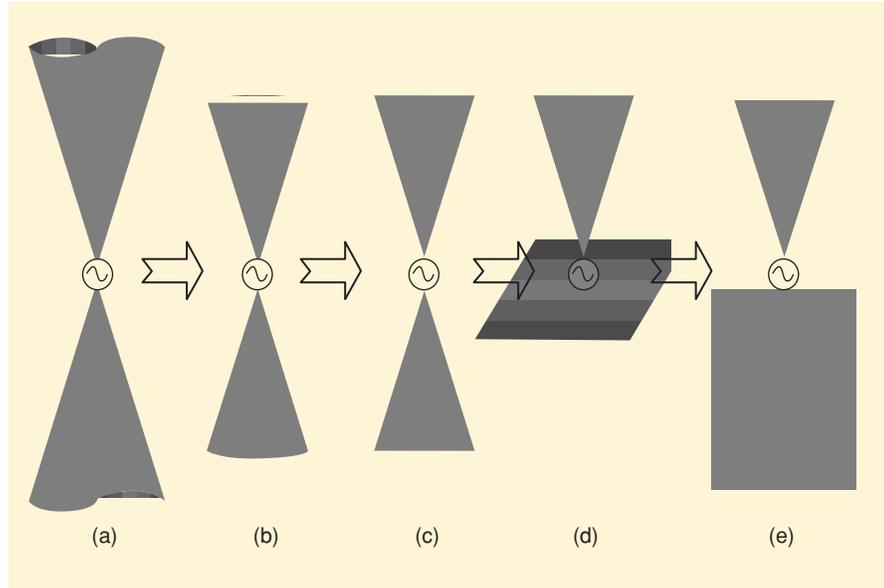


Figure 3. The evolution of planar antennas.

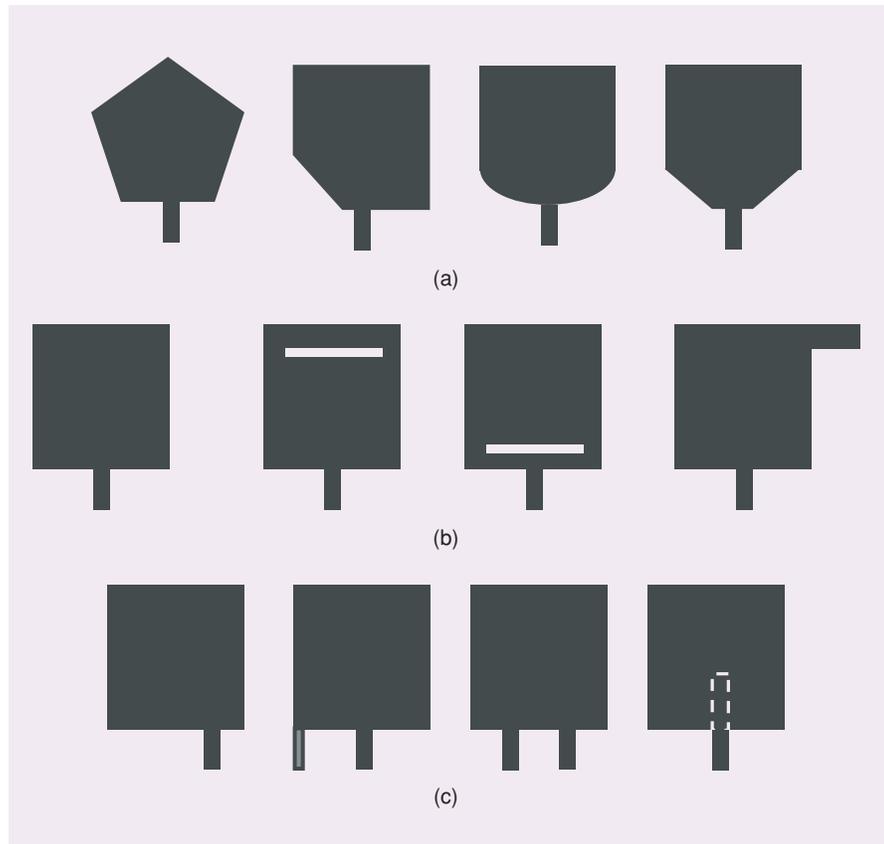
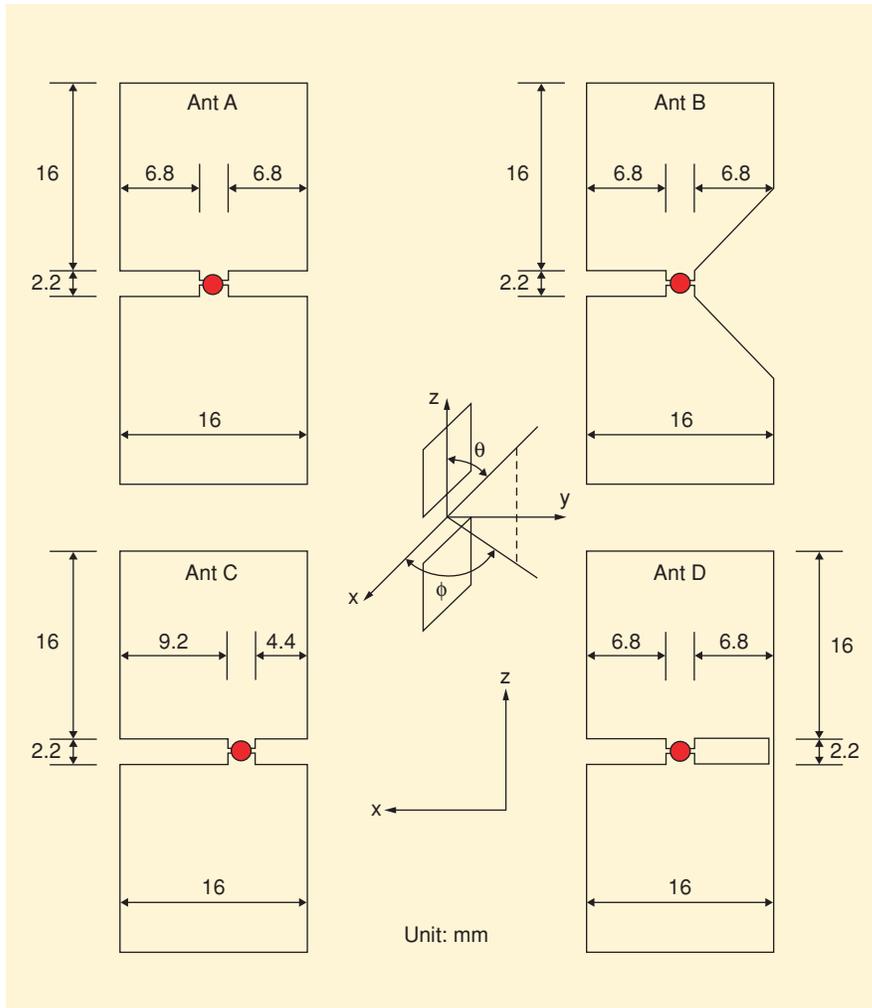


Figure 4. Planar antennas.



**Figure 5.** The square dipole and its variations.

Figure 2 shows a pair of discone antennas developed at the Institute for Infocomm Research (I<sup>2</sup>R), Singapore, for UWB applications. The discone antennas are capable of providing the well-matched impedance response and gain of  $\sim 2$  dBi covering the UWB bandwidth of 3.1–10.6 GHz. The antenna has a diameter of 35 mm and a height of 27 mm. It is suitable for UWB channel measurements and applications where omnidirectional radiation is required.

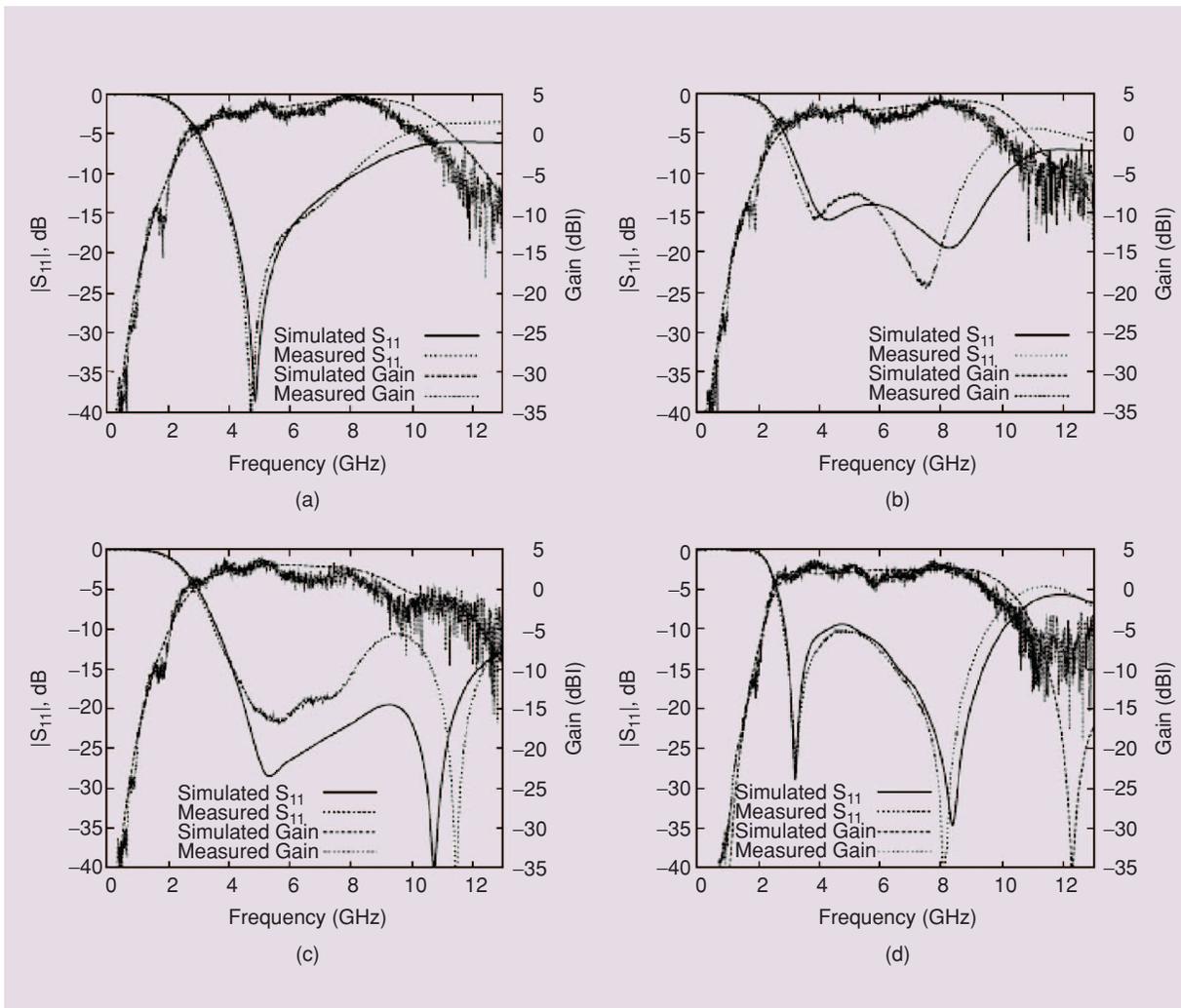
The bowtie antenna, the flat version of the biconical antennas, was presented [20] as shown in Figure 3(c), where a  $60^\circ$  bowtie antenna achieved a 2:1 impedance bandwidth for  $VSWR = 2:1$ . Similarly, one of the poles can be replaced with an electrically large conducting plate acting as a ground plane as shown in Figure 3(d). Furthermore, the two poles of the antenna can be of different shapes. In order to integrate the antenna into other RF circuits, the antennas can be readily printed onto a printed circuit board (PCB). In this form, the antenna can be embedded into the casing of devices. To date, planar monopoles with various radiator shapes have been proposed and investigated [24]–[47].

### Polygonal Monopoles

Figure 4 depicts several typical polygonal planar monopoles [24]–[43], which are vertically installed above a ground plane. The original design has a rectangular radiator. Usually, the antenna is able to achieve a bandwidth of about 60% for  $VSWR = 2:1$ . In order to enhance the impedance bandwidth, some methods have been suggested. First, the shape of the radiator may be varied. For example, the radiators may have a bevel or a smooth bottom or a pair of bevels for good impedance matching as shown in Figure 4(a) [24]–[34]. The optimization of the shape of the planar antenna, especially the shape of the bottom portion of the antenna, can improve the impedance bandwidth by achieving smooth impedance transition. Second, the radiators may be slotted to improve the impedance matching, especially at higher frequencies as shown in Figure 4(b) [35], [36]. The slots cut from

the radiators change the current distribution at the radiators so that the impedance at input point and current path change. Also, adding a strip asymmetrically at the top of the radiator can reduce the height of the antenna and improve impedance matching [37]. Last, Figure 4(c) shows several solutions using modified feeding structures. By optimizing the location of the feed point, the impedance bandwidth of the antenna will be further widened because the input impedance is varied with the location of the feed point [38]. A shorting pin can be used to reduce the height of the antenna, where a planar inverted L-shaped antenna is formed [39]. A dual-feed structure greatly enhanced the bandwidth, particularly at higher frequencies [40]. By means of electromagnetic coupling (EMC) between the radiator and feeding strip, good impedance matching can be achieved over a broad bandwidth [42].

Figure 5 shows four planar dipoles, namely Ant A: a dipole with a pair of center-fed square radiators, Ant B: Ant A with two bevels on the square radiators, Ant C: Ant A with a pair of offset-fed radiators, and Ant D: Ant A with a shorting pin at the edges of the radiators [43]. Figure 6 compares the simulated and measured return



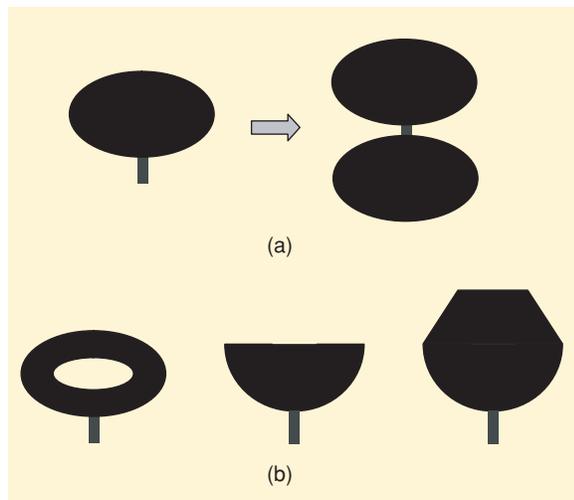
**Figure 6.** The comparison of measured and simulated return losses and gain of the square dipole and its variations shown in Figure 5.

loss and gain in the horizontal plane when the two identical dipoles are set face to face. The simple square dipole Ant A achieved impedance bandwidth of more than 40%. With bandwidth-enhancing techniques, Ants C and D are able to realize much broader bandwidths of more than 50%, which may cover the entire UWB bandwidth. Within the bandwidth, the gain response is flat as desired.

### **Elliptical Monopoles**

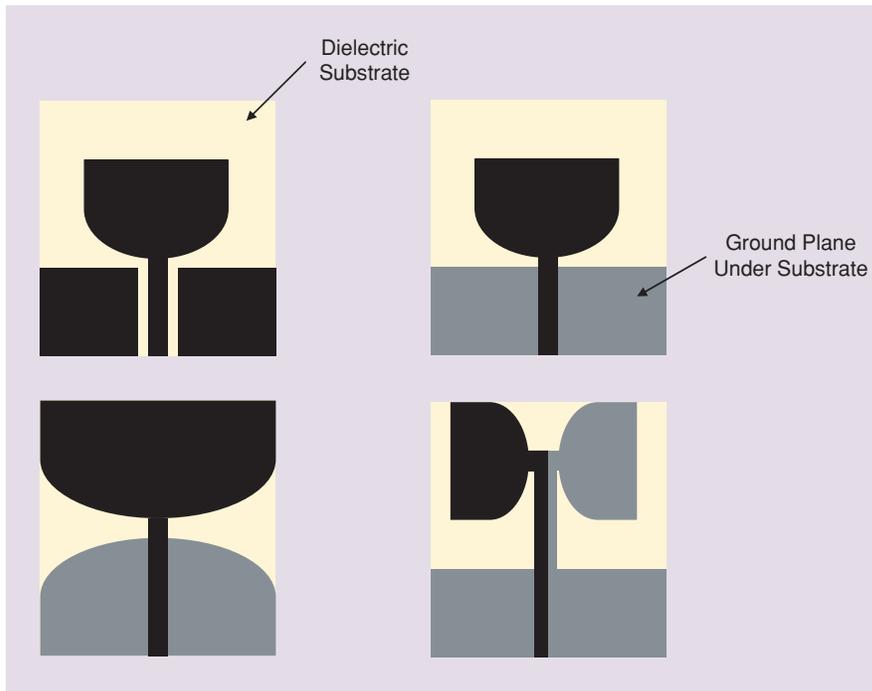
Besides the polygonal monopoles, planar monopoles of other shapes are capable of providing broad bandwidths. Figure 7 demonstrates the typical elliptical or circular planar monopoles [18], [19], [44]–[47]. Figure 3 shows that the triangular planar monopoles were first presented for broadband applications. Following that, the circular monopoles were proposed [18], [19]. Generally, the shape of the radiators can be elliptical.

By optimizing the major and minor axes of the ellipse as well as feed gap between the bottom of the ellipse and ground plane, the antenna features a high-pass imped-

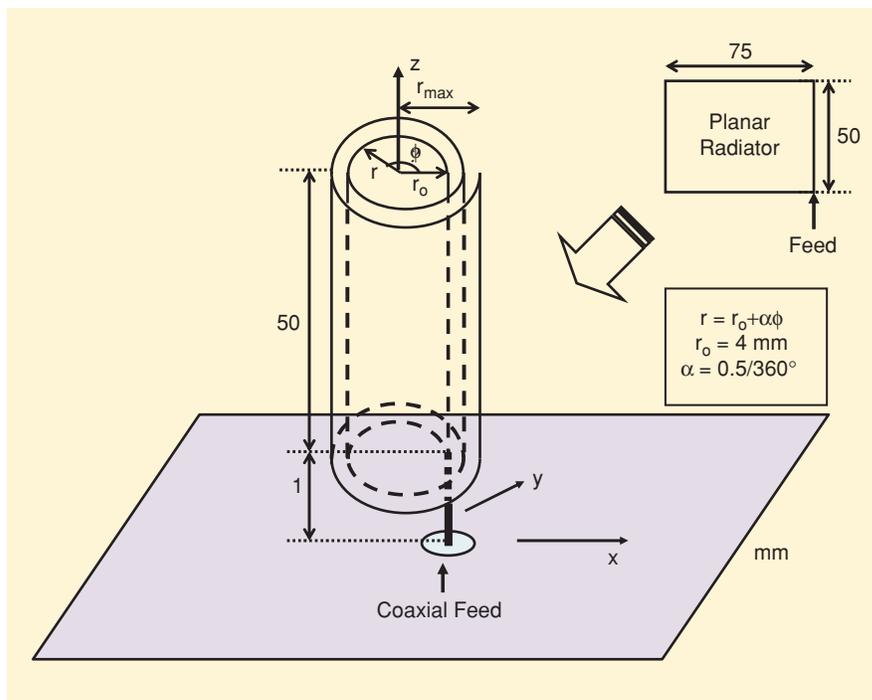


**Figure 7.** The elliptical antenna and its variations.

ance response. The broadband characteristics are due to the smooth transition between the radiator and feeding strip. From the dipole comprising two elliptical radiators,



**Figure 8.** Typical configurations of planar antenna on PCBs.



**Figure 9.** Broadband and compact roll monopole.

it is clear that the aperture between the radiators forms a transmission structure similar to a planar waveguide.

Also, the elliptical radiator can be modified for the reduction in size and enhancement in impedance bandwidths as shown in the bottom row of Figure 7.

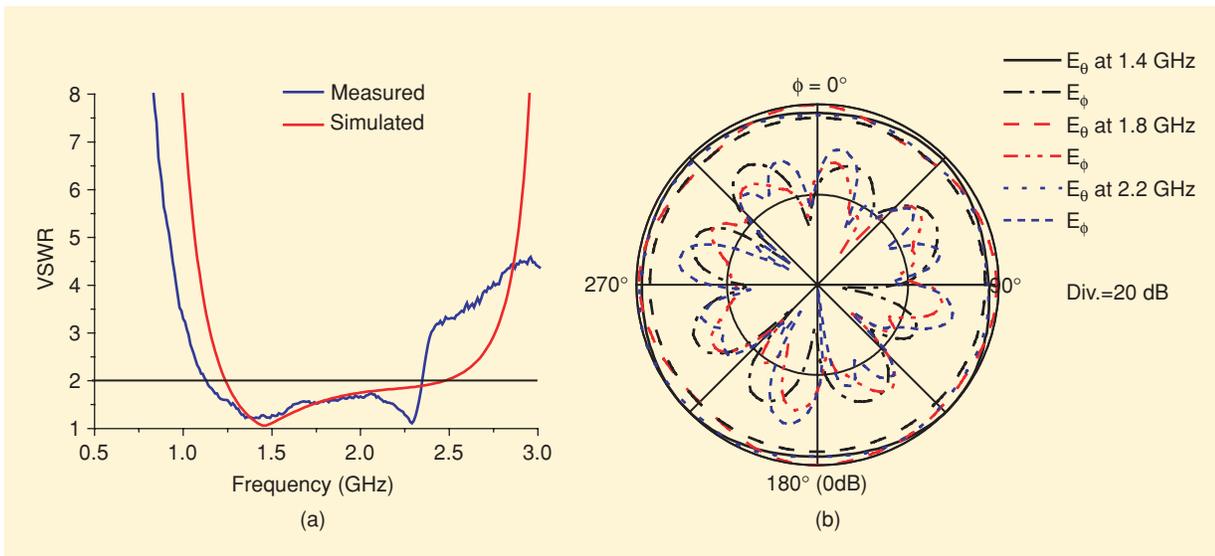
In addition, the UWB antennas printed on PCBs are more practical to implement. The antennas can be easily

integrated into other RF circuits as well as embedded into UWB devices. Figure 8 shows some typical designs [50]–[53]. Basically, the planar radiators are etched onto the dielectric substrate of the PCBs. For monopoles, the ground plane may be coplanar with the radiators or under the dielectric substrate. The ground plane may be modified to enhance the bandwidth. The radiators can be fed by a microstrip line and coaxial cable.

It should be noted that the planar monopole or dipole antennas feature broad impedance bandwidth but somewhat suffer high cross-polarization radiation levels. The large lateral size and/or asymmetric geometry of the planar radiator cause the cross-polarized radiation. Fortunately, the purity of the polarization issue is not critical, particularly for the antennas used for portable devices.

### Roll Monopoles

The planar antennas feature broad impedance bandwidths and can be easily integrated into circuits on PCBs. However, the radiation from the planar antennas may not be omnidirectional at all operating frequencies because they are not structurally rotationally symmetrical. Thick or modified cylindrical monopoles or dipoles are good options for achieving broadband omnidirectional characteristics [54]–[57]. Structurally, the thick monopoles are situated between thin cylindrical and cone monopoles. In terms of bandwidth, weight, and fabrication cost, they are unsuitable for low-cost UWB applications. Therefore, a roll monopole was presented to improve the radiation performance of a planar monopole across a broad bandwidth [24], [58]. Basically, the roll monopole is constructed by twisting the planar radiator to a roll shape as shown in Figure 9.



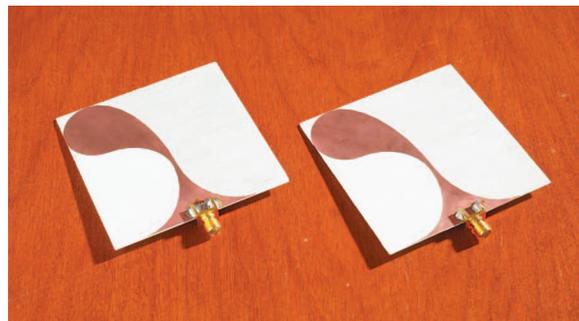
**Figure 10.** (a) Impedance response and (b) radiation response in the horizontal plane.

With the roll structure, the antenna becomes more compact and rotationally symmetrical in the horizontal plane. Due to the capacitive coupling between the adjacent layers and inductive spiral cross section, the roll monopole is also expected to achieve a broad impedance bandwidth. Figure 10 shows the impedance and radiation response of the roll monopole shown in Figure 9. The measured impedance bandwidth for  $VSWR = 2:1$  reaches 70%. The measured radiation patterns demonstrate the desired omnidirectional characteristics, with the peak gain ranging from 3.2–4.6 dBi in the horizontal plane across the achieved impedance bandwidth.

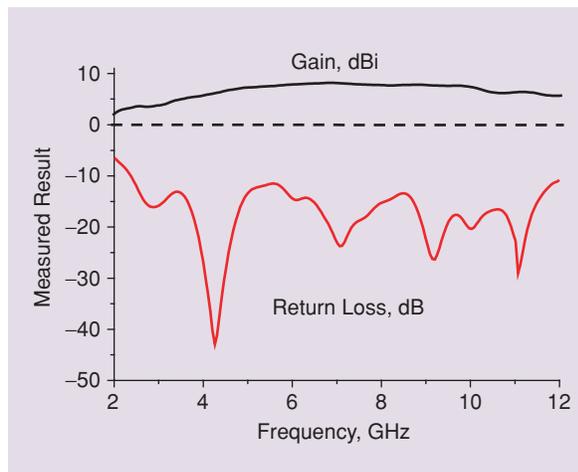
A comparison of the roll, planar, and cylindrical monopoles has revealed that the roll monopole has the merits of having a broad impedance bandwidth like a planar monopole and omnidirectional radiation like a rotationally symmetrical cylindrical monopole [59]. However, it is not easy to fabricate the roll antenna with high accuracy. Thus, in practical antenna design, the simple versions are used where studies also showed that the roll monopole is capable of providing the desirable performance in UWB applications [60].

### Antipodal Vivaldi Antenna

Besides the omnidirectional antennas mentioned above, antennas with stable directional radiation are also very important in some applications such as fixed base stations for communications as well as arrays for communications and radar systems. In some sense, it is more difficult to design an antenna with stable radiation performance across an ultrawideband because of the change in the current distribution of the radiators. Tapered slot antennas (TSAs), which are considered to be a type of endfire traveling-wave antenna, can achieve stable radiation performance across a broad operating bandwidth. Linear



**Figure 11.** The antipodal Vivaldi antenna developed at I<sup>2</sup>R.



**Figure 12.** Measured impedance and gain response across the UWB bandwidth.

TSAs and Vivaldi antennas play the key roles in TSA design in terms of design and performance. Much effort has been devoted to linear TSAs or Vivaldi antennas [61]–[65]. Here, the antipodal Vivaldi antennas (AVAs) are exemplified for UWB applications [24], [66]–[69].

Recently, extremely broad frequency ranges have been allocated for UWB imaging, communications, and radar and localization systems.

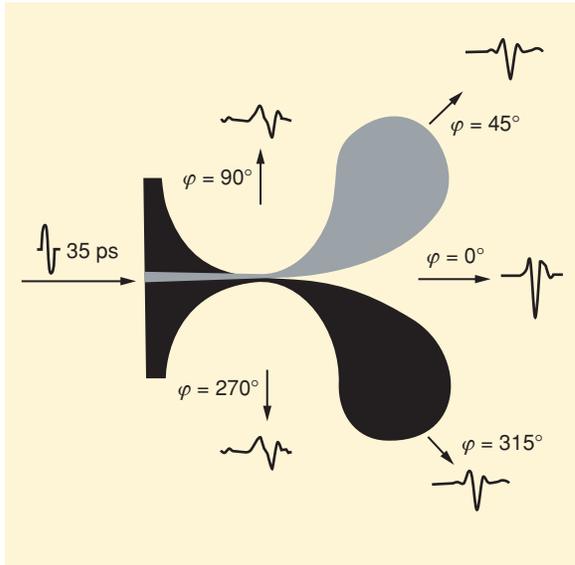


Figure 13. Measured waveforms of radiated pulses when the antenna is driven by a monocycle pulse with a width of 35 ps.

Figure 11 depicts an antipodal Vivaldi antenna. With the broadband impedance transition, a conventional Vivaldi antenna is fed by a microstrip line. The ends of the conventional antipodal Vivaldi antenna are extended by adding two semicircles, which extend the lower edge frequency and improve the impedance response. Figure 12 shows the measured impedance and gain response of the antenna shown in Figure 11 within the UWB band. The broadband characteristics for both impedance and radiation performance have been observed. Figure 13 demonstrates the waveforms of the radiated pulses in different directions in the E plane when the antenna was excited by a monocycle with a pulse width of 35 ps.

### Planar UWB Antenna Close to Human Head

Recently, many research and development activities have been focused on the applications of UWB systems. The UWB antennas applied in some practical scenarios have been investigated. The following describes the investigation of the proximity effects of a human head on the radiation of the UWB antenna.

The proximity effects of a human head on a planar UWB antenna are considered. This application is related to the case that a wireless UWB device such as an earphone (which the UWB antenna is embedded into) is worn near an ear. Due to the low power used in UWB systems, the effect of radiation from the UWB antenna on the human head can be ignored. The influence of the human head on the performance of antennas close to the human head is of interest [70], [71].

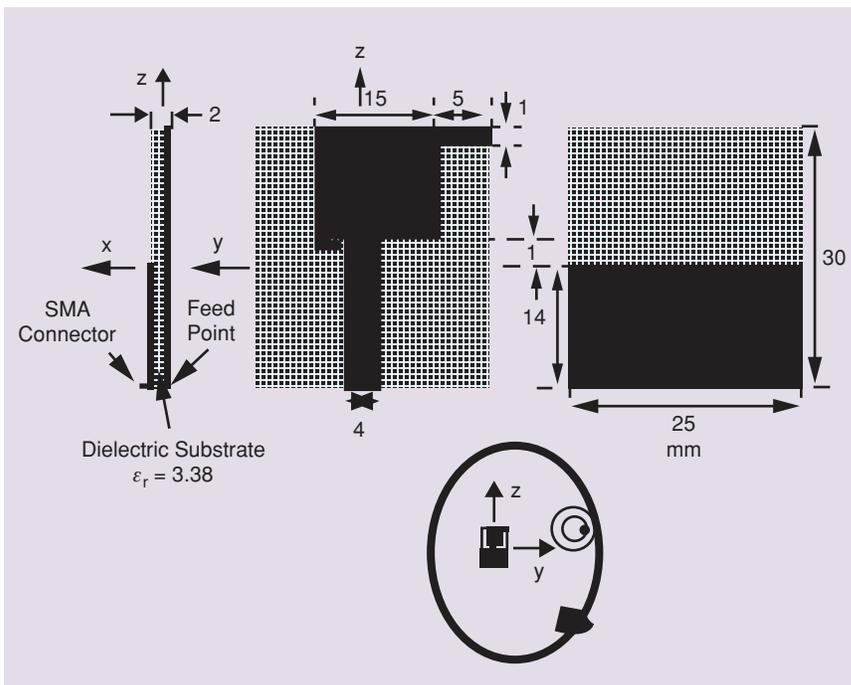


Figure 14. Geometry of the printed PCB antenna and the position of the antenna close to the human head.

A planar antenna was designed and etched on a 25-mm × 30-mm PCB with a thickness of 1.5 mm and dielectric constant  $\epsilon_r = 3.38$  as shown in Figure 14. The radiator comprises a 15-mm × 15-mm square joined by a horizontal strip of 5 mm × 1 mm on the top of the square. The bottom of the square is fed by a 50-Ω microstrip line of a 4-mm width and 15-mm length, which was etched on the same side of the PCB as the radiator. The 25-mm × 14-mm system ground plane was etched on the other side of the PCB under the microstrip line. The feed gap between the radiator and the upper edge of the system ground plane is 1 mm. The left edge of the feeding strip is offset by 3 mm from the left edge of the radiator to achieve good impedance matching.

In the study, a numerical human head model was used. The anatomical human head with two shoulders used in XFDTD is composed of 27 types of biological tissues, including mainly the skin, bone, brain, muscle, humor, lens, and cornea (as shown in Figure 15). The dielectric constant and conductivity of the tissues are frequency dependent. The model can be considered as an irregular, inhomogeneous, and lossy dielectric object.

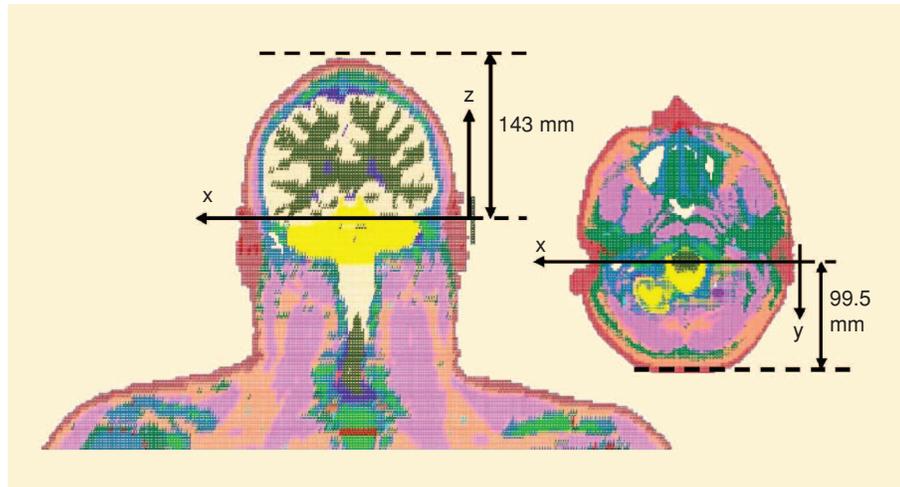


Figure 15. A human head model and its orientation near a human head.

In the FDTD simulations, the gap between the antenna and the head varies from 2 mm to 4 mm, and the mesh cell size of  $1 \text{ mm} \times 1 \text{ mm} \times 1 \text{ mm}$  with respect to  $x$ ,  $y$ , and  $z$  axes and time step of 1.926 ps are used to meet the two main constraints for the highest frequency of 10.6 GHz in the UWB band. For the achieved convergence, the impedance performance was calculated using a Gaussian monocycle of a 32-time step pulse width using 3,000 time steps. The sinusoidal source centered at 3 GHz, 7 GHz, and 10 GHz was used to simulate the radiation patterns using 2,000 time steps.

Figure 16 compares the simulated return losses of the antenna in free space and with the head. It is clear that the presence of the head slightly affects the impedance matching.

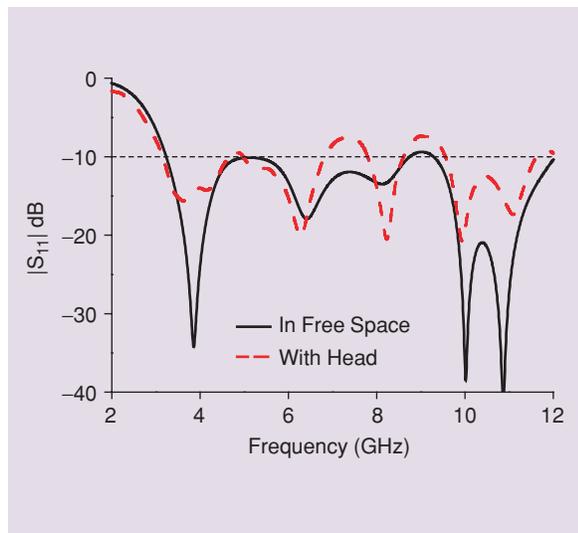


Figure 16. A comparison of return losses of the antenna in free space and near the human head.

However, Figure 17 demonstrates the severe effect of the human head on the radiation performance by calculating the gain along the  $x$ -axis and observing

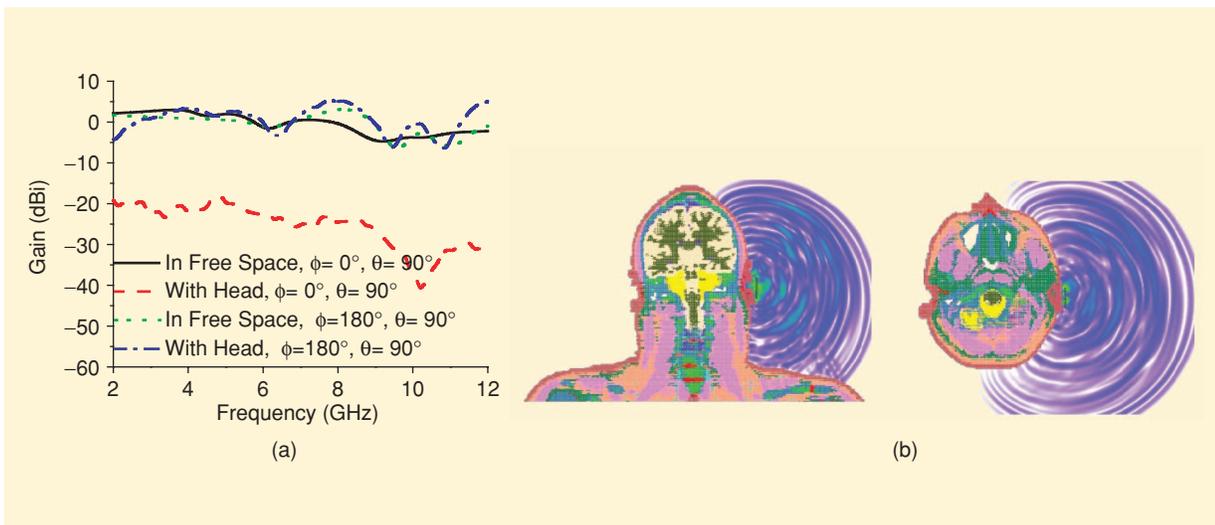


Figure 17. (a) A comparison of gain of the antenna in free space and near the human head. (b) The distribution of electric fields in time domain (321 time steps).

the field distribution in time domain. It can be concluded that the human head slightly affects the impedance matching of the antenna, but it has significant effects on the gain and radiation patterns. The human head blocks the radiation greatly.

## Conclusions

Due to the unique requirements of microwave UWB applications, the antenna design has become a critical issue in system design. Among many broadband options, planar antennas and their variations have demonstrated their attractive merits, such as broad bandwidths for impedance and radiation, stable phase response, easy fabrication and integration with other RF circuits, small size, light weight, and embeddable configuration. Therefore, much effort has been made to investigate characteristics of planar antennas and their applications in forthcoming UWB systems. In the future, the work may focus more on two aspects. One may be the fundamental issues, such as understanding the radiation mechanism in time domain, fast time-domain algorithms, miniaturizing technology, nondispersive design, and object (such as human body) proximity effect. The other one may be the antenna and array designs to meet the system requirements, such as small size, low cost, embedded/conformal configuration, and high gain.

There have been many books on the market which are related to UWB systems and antennas and good for further reading [24], [72]–[75].

## Acknowledgments

The authors would like to thank Dr. Ning Yang (Motorola Inc. Singapore), Dr. Dong Mei Shan (National University of Singapore), Dr. Michael Y. W. Chia (Institute for Infocomm Research, Singapore), and Dr. Wee Kian Toh (Institute for Infocomm Research, Singapore) for their contributions to this research work in one way or another.

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