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# Planar Antennas

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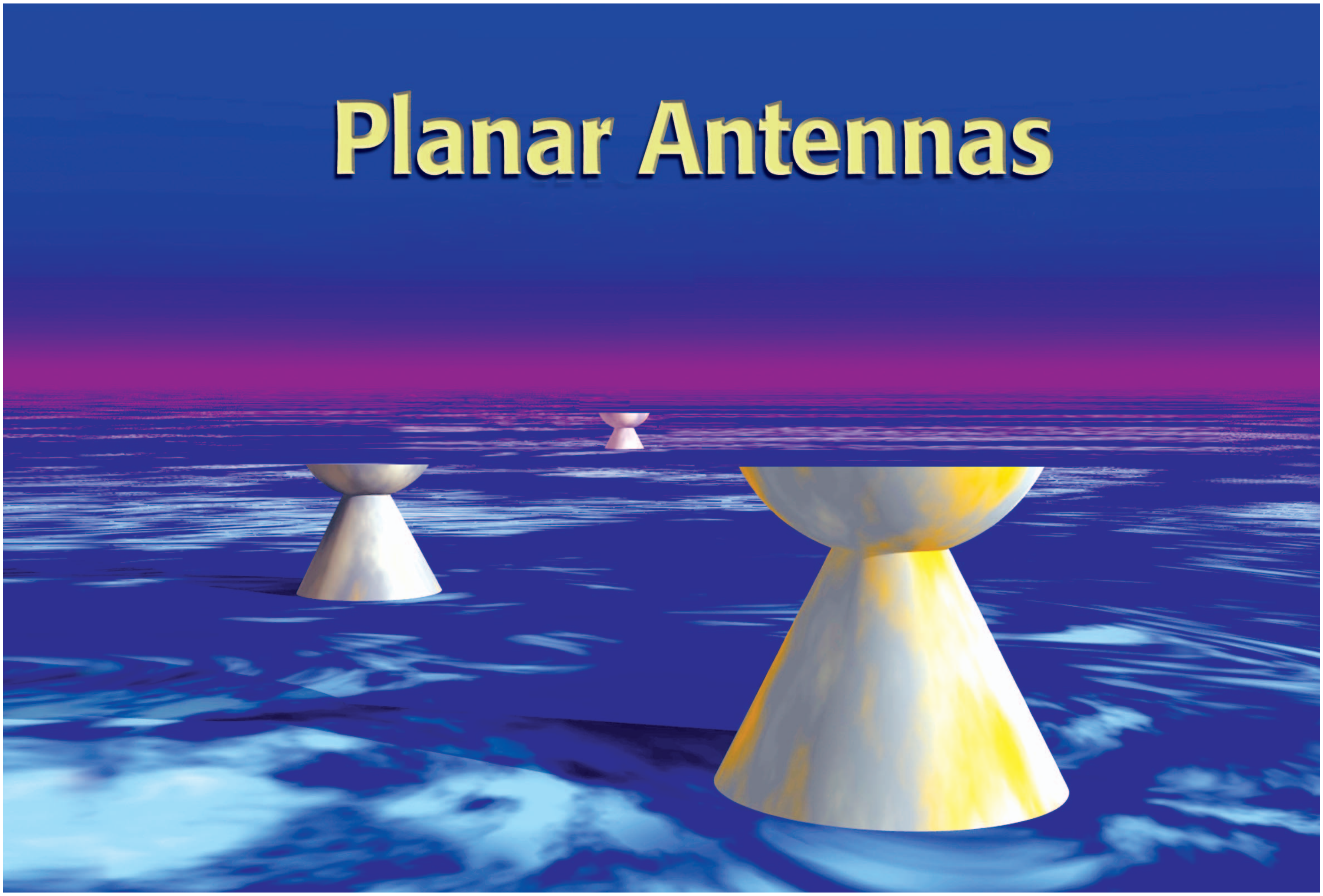



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The release of an extremely wide spectrum of 3.1–10.6 GHz for commercial applications has greatly spurred the research and development of microwave ultrawideband (UWB) technology for communications, imaging, radar, and localization applications. In 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 radiation 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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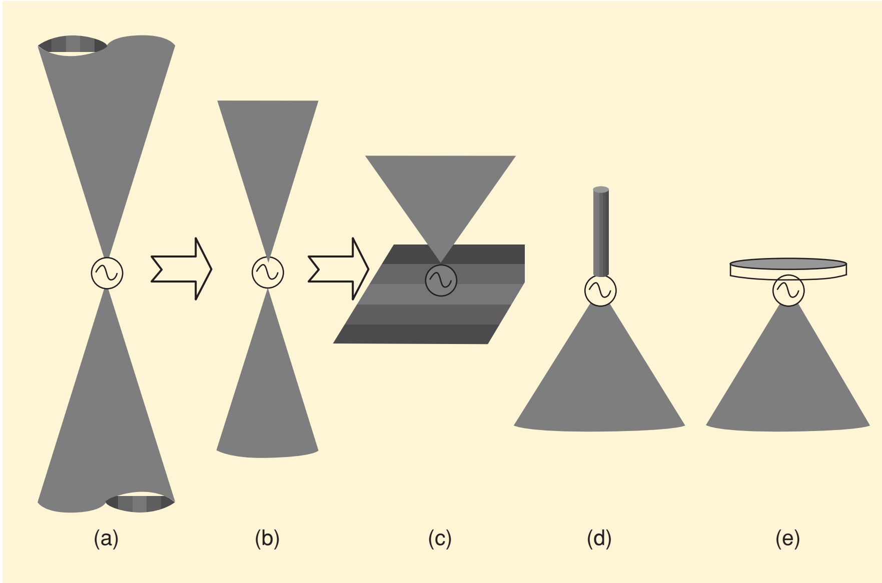

**Figure 1.** *The evolution of conical antennas.*

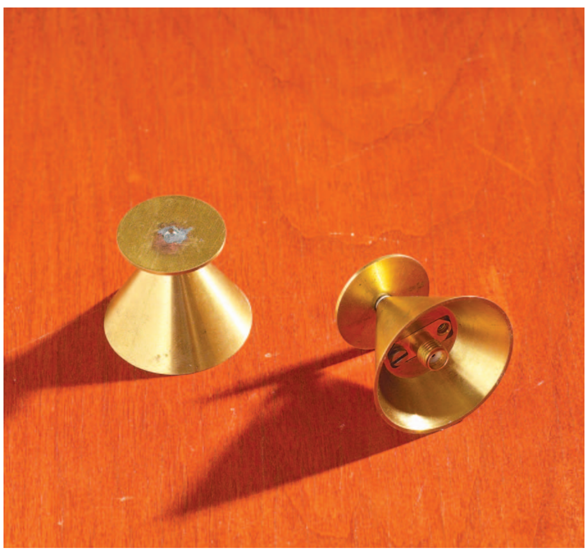
**Figure 2.** *The discone antenna developed at $I^2R$.*

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, discone 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 impulsed 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 implused 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° finite cone [Figure 1(d)] or disc, a 90° finite cone [Figure 1(e)]. The discone antennas have been widely applied in UWB systems, particularly for channel measurements and system testing [23].

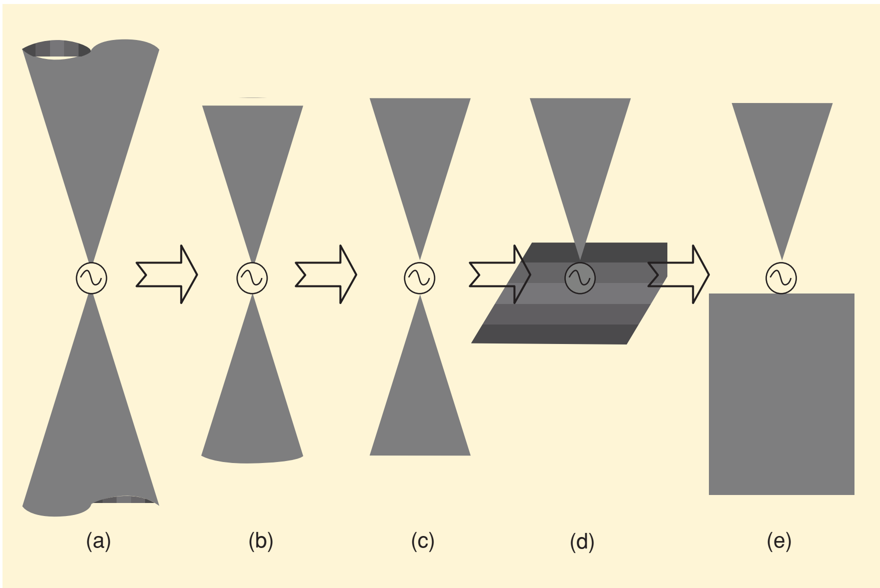

**Figure 3.** *The evolution of planar antennas.*

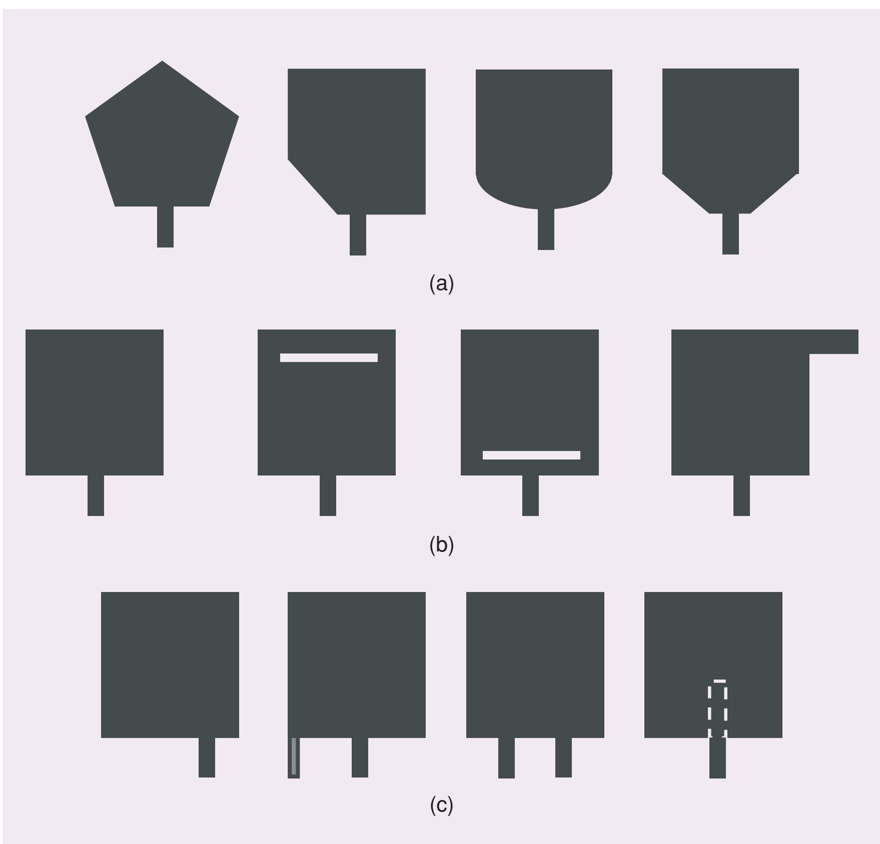

**Figure 4.** *Planar antennas.*

## *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

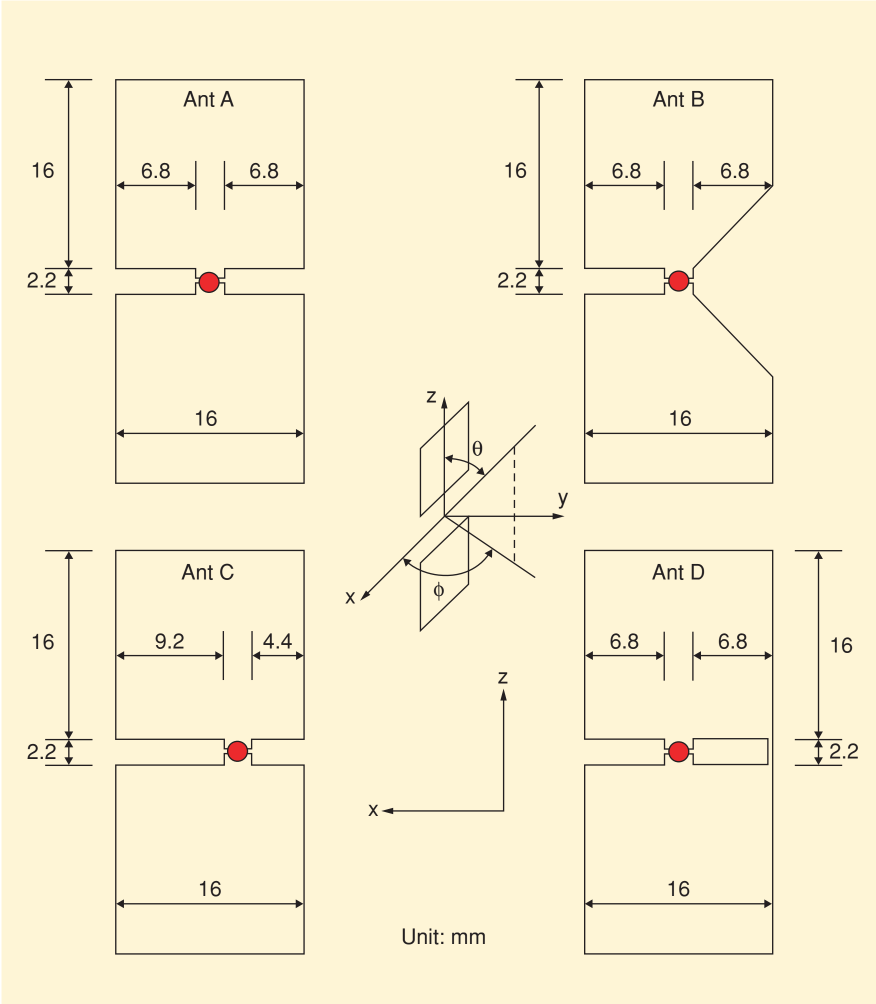


**Figure 5.** *The square dipole and its variations.*

Figure 2 shows a pair of discone antennas developed at the Institute for Infocomm Research ($I^2R$), Singapore, for UWB applications. The discone antennas are capable of providing the well-matched impedance response and gain of ~2dBi 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° 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].

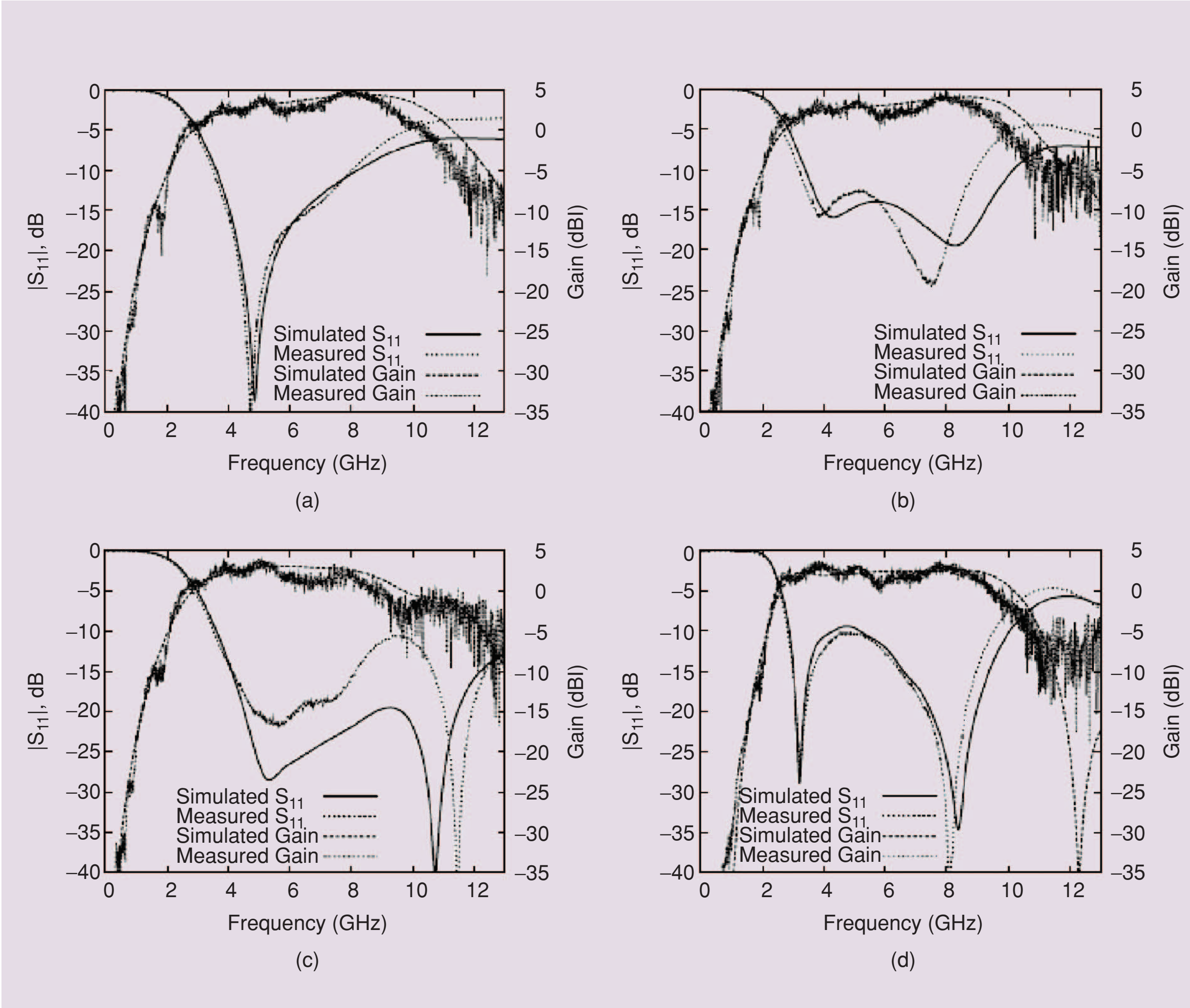


**Figure 6.** *The comparison of measured and simulated return losses and gain of the square dipole and its variations shown in Figure 5.*

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.

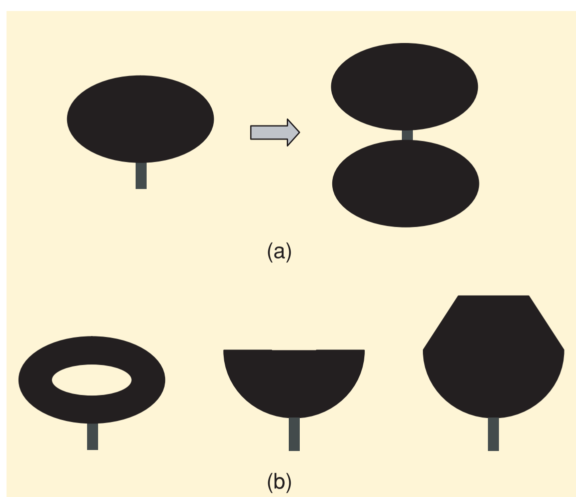


**Figure 7.** *The elliptical antenna and its variations.*

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

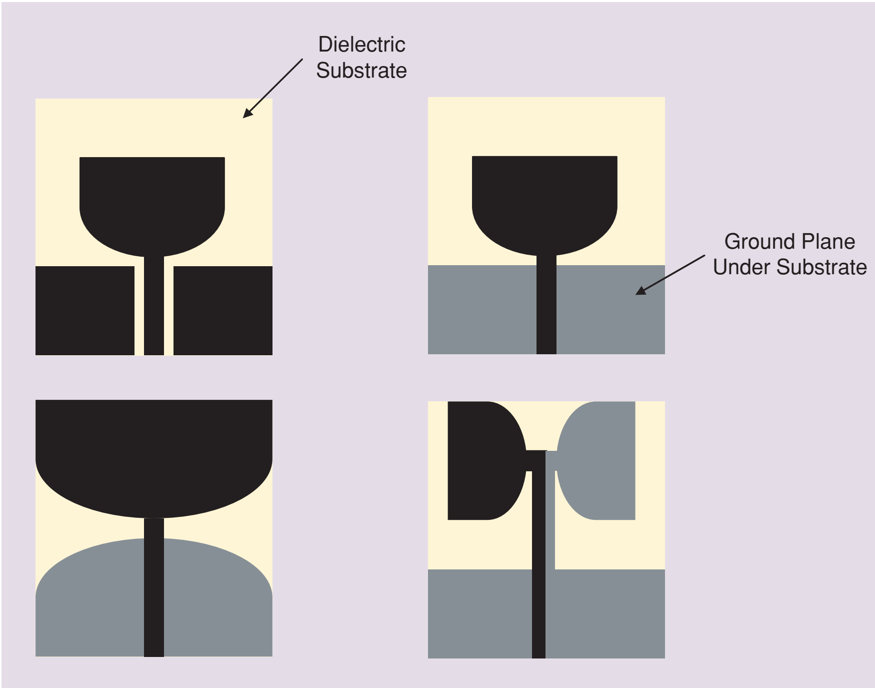


**Figure 8.** *Typical configurations of planar antenna on PCBs.*

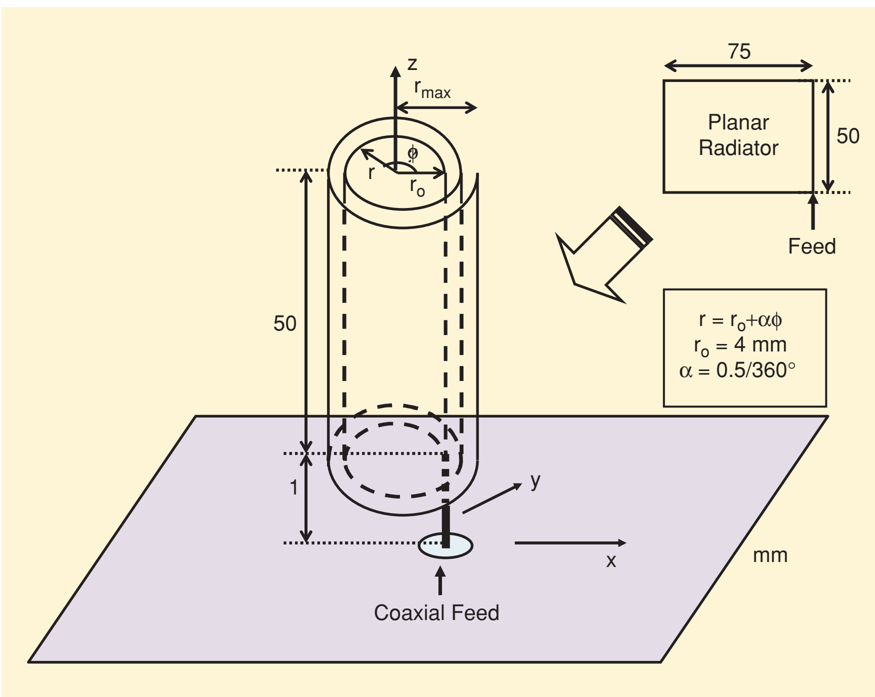


**Figure 9.** *Broadband and compact roll monopole.*

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 rotationallysymmetrical. 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.

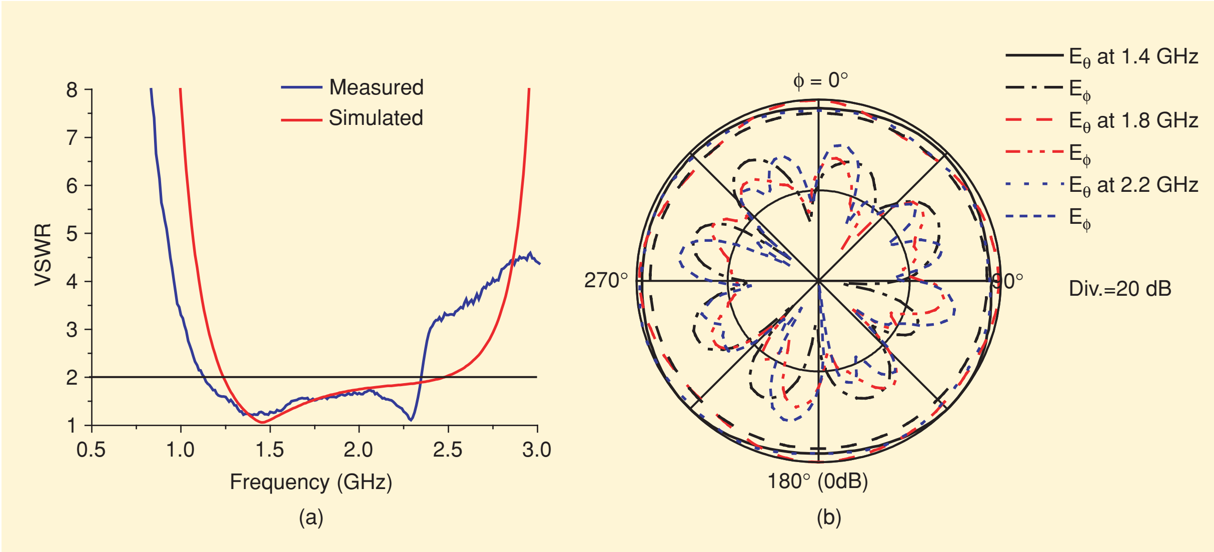


**Figure 10.** *(a) Impedance response and (b) radiation response in the horizontal plane.*

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

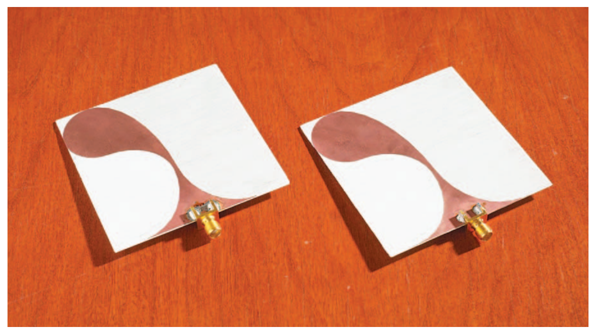

**Figure 11.** *The antipodal Vivaldi antenna developed at $I^2R$.*

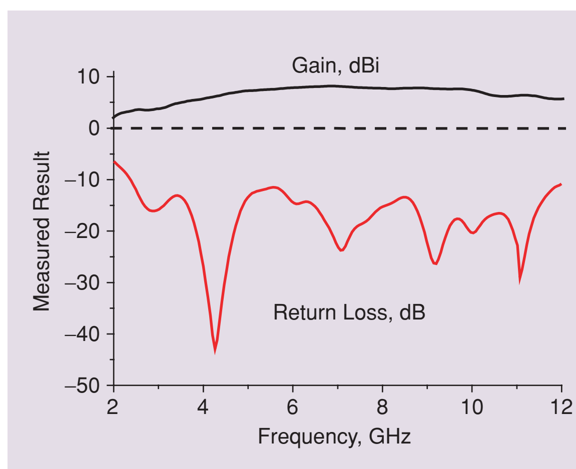


**Figure 12.** *Measured impedance and gain response across the UWB bandwidth.*

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.**

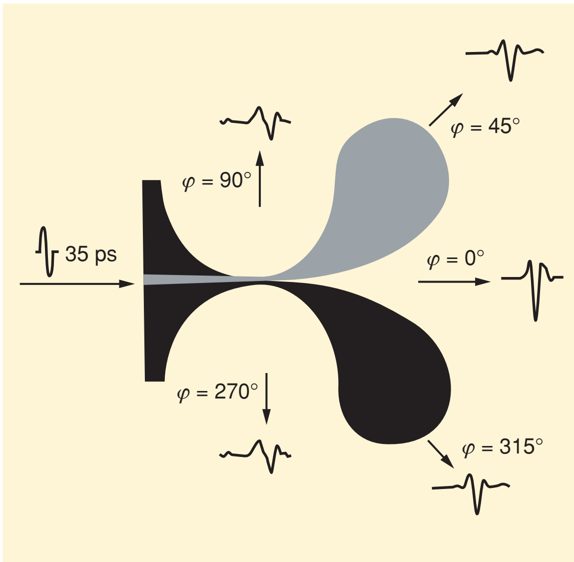


**Figure 13.** *Measured waveforms of radiated pulses when the antenna is driven by a monocycle pulse with a width of 35 ps.*

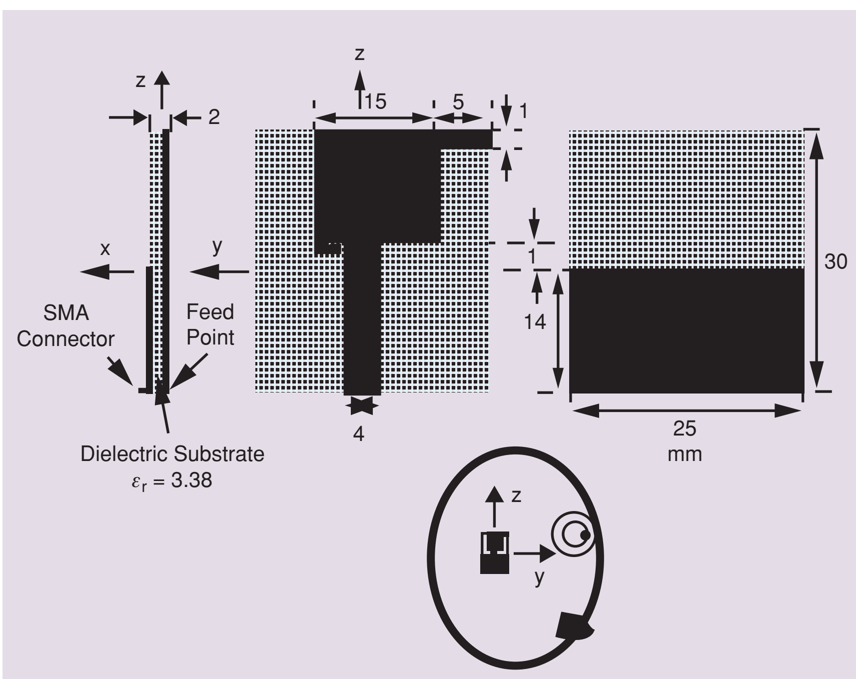


**Figure 14.** *Geometry of the printed PCB antenna and the position of the antenna close to the human head.*

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].

A planar antenna was designed and etched on a 25-mm × 30-mm PCB with a thickness of 1.5 mm and dielectric constant $\varepsilon_r = 3.38$ 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.

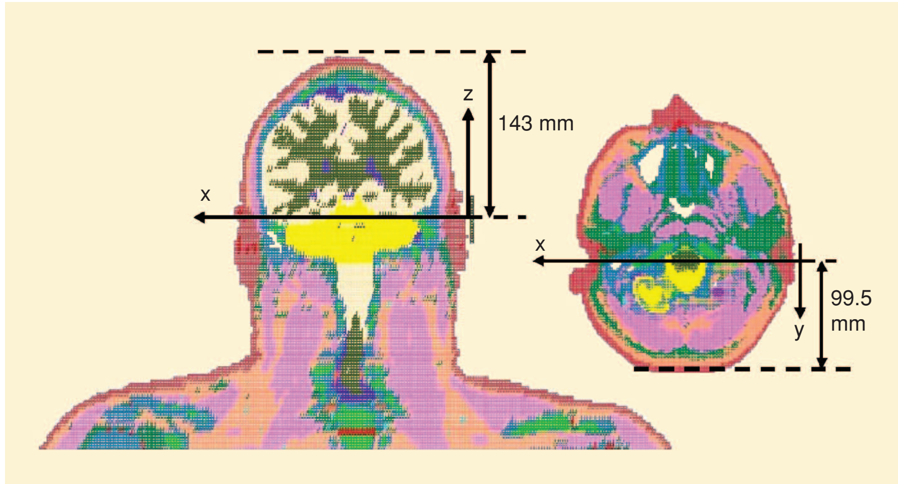


**Figure 15.** *A human head model and its orientation near a human head.*

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 mm × 1 mm × 1 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.

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

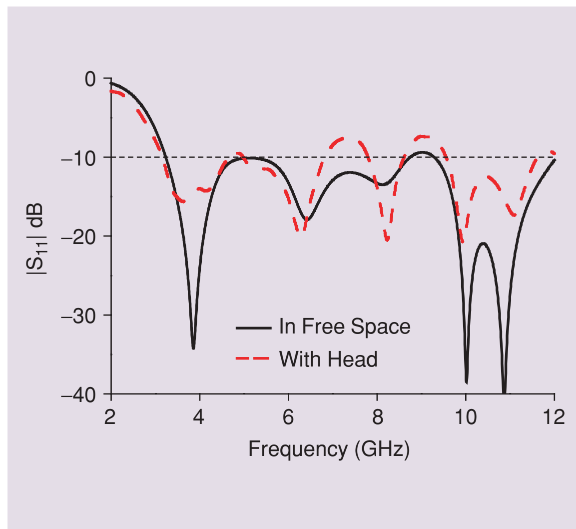


**Figure 16.** *A comparison of return losses of the antenna in free space and near the human head.*

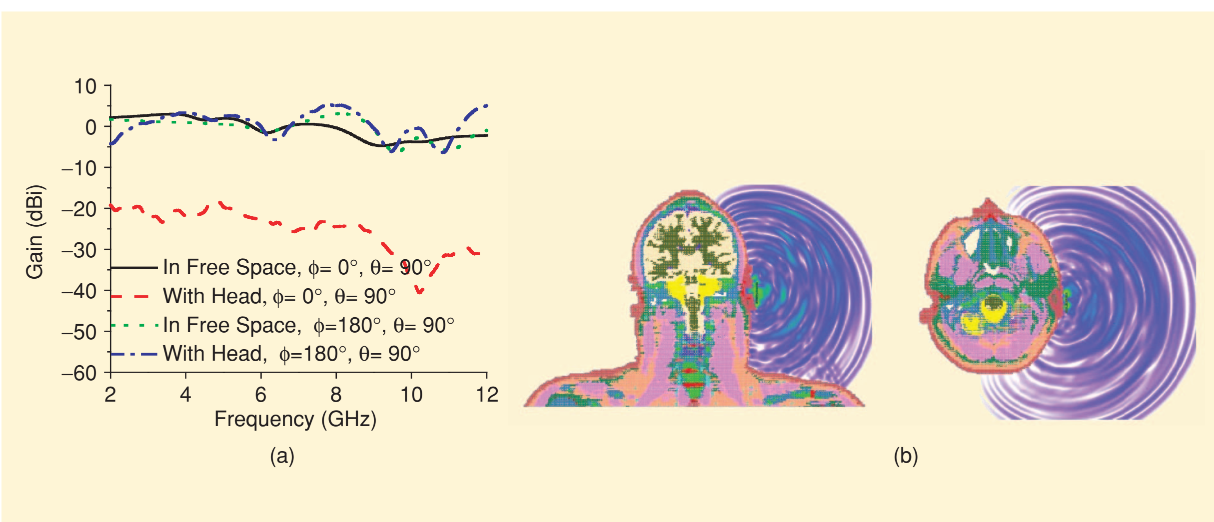


**Figure 17.** *(a) A comparison of gain of the antenna in free space and near the human head. (b) The distribution of electric fields in time domain (321 time steps).*

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].


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## References


[1] "First order and report, revision of part 15 of the commission's rules regarding UWB transmission systems," Fed Commun. Comm., FCC 02-48, Apr. 22, 2002.

[2] M. Kanda, "Transients in a resistively loaded linear antennas compared with those in a conical antenna and a TEM horn," *IEEE Trans. Antennas Propagat.*, vol. 28, no. 1, pp. 132–136, Jan. 1980.

[3] K.L. Shlager, G.S. Smith, and J.G. Maloney, "Accurate analysis of TEM horn antennas for pulse radiation," *IEEE Trans. Electromagn. Compat.*, vol. 38, no. 3, pp. 414–423, Aug. 1996.

[4] B. Scheers, M. Acheroy, and A. Vander Vorst, "Time-domain simulation and characterisation of TEM horns using a normalised impulse response," *Proc. Inst. Elect. Eng. Microw., Antennas Propagat.*, vol. 147, no. 6, pp. 463–468, Dec. 2000.

[5] L.T. Chang and W.D. Burnside, "An ultrawide-bandwidth tapered resistive TEM horn antenna," *IEEE Trans. Antennas Propagat.*, vol. 48, no. 12, pp. 1848–1857, Dec. 2000.

[6] R.T. Lee and G.S. Smith, "On the characteristic impedance of the TEM horn antenna," *IEEE Trans. Antennas Propagat.*, vol. 52, no. 1, pp. 315–318, Jan. 2004.

[7] P.E. Mayes, "Frequency-independent antennas and broad-band derivatives thereof," *Proc. IEEE*, vol. 80, no. 1, pp. 103–112, Jan. 1992.

[8] T.W. Hertel and G.S. Smith, "On the dispersive properties of the conical spiral antenna and its use for pulsed radiation," *IEEE Trans. Antennas Propagat.*, vol. 51, no. 7, pp. 1426–1433, July 2003.

[9] J.D. Kraus, *Antennas,* 2nd ed. New York: McGraw-Hill, 1988, pp. 340–358.

[10] C.W. Harrison, Jr. and C.S. Williams, Jr., "Transients in wide-angle conical antennas," *IEEE Trans. Antennas Propagat.*, vol. 13, no. 2, pp. 236–246, Mar. 1965.

[11] S.S. Sandler and R.W.P. King, "Compact conical antennas for wide-band coverage," *IEEE Trans. Antennas Propagat.*, vol. 42, no. 3, pp. 436–439, Mar. 1994.

[12] S.N Samaddar and E.L. Mokole, "Biconical antennas with unequal cone angles," *IEEE Trans. Antennas Propagat.*, vol. 46, no. 2, pp. 181–193, Feb. 1998.

[13] T.T. Wu and R.W.P. King, "The cylindrical antenna with nonreflecting resistive loading," *IEEE Trans. Antennas Propagat.*, vol. 13, no. 3, pp. 369–373, May 1965.

[14] D.L. Senguta and Y.P. Liu, "Analytical investigation of waveforms radiated by a resistively loaded linear antenna excited by a Gaussian pulse," *Radio Sci.*, vol. 9, no. 3, pp. 621–630, June 1974.

[15] J.G. Maloney and G.S. Smith, "A study of transient radiation from the Wu-King resistive monopole—FDTD analysis and experimental measurements," *IEEE Trans. Antennas Propagat.*, vol. 41, no. 5, pp. 668–676, May 1993.

[16] H. Meinke and F.W. Gundlach, *Taschenbuch der Hochfrequenztechni.* Berlin: Springer-Verlag, 1968, pp. 531–535.

[17] G. Dubost and Zisler, *Antennas a Large Bande*. Paris, France: Masson, 1976, pp. 128–129, .

[18] S. Honda, M. Ito, H. Seki, and Y. Jinbo, "A disk monopole antenna with 1:8 impedance bandwidth and omnidirectional radiation pattern," in *Proc. Int. Symp. Antennas Propagation.*, Sapporo, Japan, 1992, pp. 1145–1148.

[19] M. Hammoud, P. Poey, and F. Colombel, "Matching the input impedance of a broadband disc monopole," *Electron. Lett.*, vol. 29, no. 4, pp. 406–407, 1993.

[20] G.H. Brown and O.M. Woodward, "Experimentally determined radiation characteristics of conical and triangular antennas," *RCA Rev.*, vol. 13, pp. 425–452, Dec. 1952.

[21] M.J. Ammann and Z.N. Chen, "Wideband monopole antennas for multi-band wireless systems," *IEEE Antennas Propagat. Mag.*, vol. 45, no. 2, pp. 146–150, Apr. 2003.

[22] Z.N. Chen, X.H. Wu, N. Yang, and M.Y.W. Chia, "Considerations for source pulses and antennas in UWB radio systems," *IEEE Trans. Antennas Propagat.*, vol. 52, no. 7, pp. 1739–1748, July 2004.

[23] X.M. Qing and Z.N. Chen, "Transfer functions measurement for UWB antenna," in *Proc. IEEE Int. Symp. Antennas Propagation*, Monterey, CA, June 2004, pp. 2532–2535.

[24] Z.N. Chen and M.Y.W. Chia, *Broadband Planar Antennas: Design and Applications*. West Sussex, UK: Wiley, 2006.

[25] K.L. Shlager, G.S. Smith, and J.G. Maloney, "Optimization of bow-tie antennas for pulse radiation," *IEEE Trans. Antennas Propagat*, vol. 42, no. 7, pp. 975–982, July 1994.

[26] D. Lamensdorf and L. Susman, "Baseband-pulse-antenna techniques," *IEEE Antennas Propagat. Mag.*, vol. 36, pp. 20–30, Feb. 1994.

[27] J.A. Evans and M.J. Ammann, "Planar trapezoidal and pentagonal monopoles with impedance bandwidths in excess of 10:1," in *Proc. IEEE Int. Symp. Antennas Propagation.*, Orlando, FL, 1999, pp. 1558–1561.

[28] M.J. Ammann, "Square planar monopole antenna," *IEE Nat. Conf. Antennas Propagat.*, York, England, pp. 37–40, 1999.

[29] Z.N. Chen, "Impedance characteristics of planar bow-tie-like monopole antennas," *Electron. Lett.*, vol. 36, no. 13, pp. 1100–1101, 2000.

[30] M.J. Ammann, "Impedance bandwidth of the square planar monopole," *Microw. Opt. Technol. Lett.*, vol. 24, no. 3, pp. 185–187, 2000.

[31] Z.N. Chen and M.Y.W. Chia, "Impedance characteristics of trapezoidal planar monopole antenna," *Microw. Opt. Technol. Lett.*, vol. 27, no. 2, pp. 120–122, 2000.

[32] Z.N. Chen, "Experiments on input impedance of tilted planar monopole antennas," *Microw. Opt. Technol. Lett.*, vol. 26, no. 3, pp. 202–204, 2000.

[33] X.H. Wu, Z.N. Chen, and N. Yang, "Optimization of planar diamond antenna for single/multi-band UWB wireless communications," *Microw. Opt. Technol. Lett.*, vol. 42, no. 6, pp. 451–455, 2004.

[34] M.J. Ammann and Z.N. Chen, "A wideband shorted planar monopole with bevel," *IEEE Trans. Antennas Propagat.*, vol. 51, no. 4, pp. 901–903, 2003.

[35] Z.N. Chen, M.J. Ammann, and M.Y.W. Chia, "Broadband square annular planar monopoles," *Microw. Opt. Technol. Lett.*, vol. 36, no. 6, pp. 449–454, Mar. 2003.

[36] D. Valderas, J. Meléndez, I. Sancho, "Some design criteria for UWB planar monopole antennas: Application to a slotted rectangular monopole," *Microw. Opt. Technol. Lett.*, vol. 46, no. 1, pp. 6–11, July 2005.

[37] A. Cai, T.S.P. See, and Z.N. Chen, "Study of human head effects on UWB antenna," in *Proc. IEEE Intl. Workshop on Antenna Technology (iWAT)*, Singapore, Mar. 7–9, 2005, pp. 310–313.

[38] M.J. Ammann and Z.N. Chen, "An asymmetrical feed arrangement for improved impedance bandwidth of planar monopole antennas," *Microw. Opt. Technol. Lett.*, vol. 40, no. 2, pp. 156–158, 2004.

[39] E. Lee, P.S. Hall, and P. Gardner, "Compact wideband planar monopole antenna," *Electron. Lett.*, vol. 35, no. 25, pp. 2157–2158, Dec. 1999.

[40] E. Antonino-Daviu, M. Cabedo-Fabres, M. Ferrando-Bataller, and A. Valero-Nogueira, "Wideband double-fed planar monopole antennas," *Electron. Lett.*, vol. 39, no. 23, pp. 1635–1636, Nov. 2003.

[41] Z.N. Chen and M.Y.W Chia, "Impedance characteristics of EMC triangular planar monopoles," *Electron. Lett.*, vol. 37, no. 21, pp. 1271–1272, 2001.

[42] Z.N. Chen, M.J. Ammann, M.Y.W. Chia, and T.S.P. See, "Circular annular planar monopoles with EM coupling," *Proc. Inst. Elect. Eng. Microw. Antennas, Propagat.*, vol. 150, no. 4, pp. 269–273, Aug. 2003.

[43] X.H. Wu and Z.N. Chen, "Comparison of planar dipoles in UWB applications," *IEEE Trans. Antennas Propagat.*, vol. 53, no. 6, pp. 1973–1983, 2005.

[44] N.P. Agrawall, G. Kumar, and K.P. Ray, "Wide-band planar monopole antenna," *IEEE Trans. Antennas Propagat.*, vol. 46, no. 2, pp. 294–295, Feb. 1998.

[45] C.Y. Huang and W.C. Hsia, "Planar elliptical antenna for ultra-wideband communications," *Electron. Lett.*, vol. 41, no. 6, pp. 296–297, Mar. 2005.

[46] Z.N. Chen, M.J. Ammann, and M.Y.M. Chia, "Annular circular planar monopole antennas," *Proc. Inst. Elect. Eng. Microw. Antennas, Propagat.*, vol. 149, no. 4, pp. 200–203, Aug. 2002.

[47] S.Y. Suh, W.L. Stutzman, and W.A. Davis, "A new ultrawideband printed monopole antenna: the planar inverted cone antenna (PICA)," *IEEE Trans. Antennas Propagat.*, vol. 52, no. 5, pp. 1361–1364, May 2004.

[48] J.W. Lee, C.S. Cho, and J. Kim, "A new vertical half disc-loaded ultra-wideband monopole antenna (VHDMA) with a horizontally top-loaded small disc," *Antennas Wireless Propagat. Lett.*, vol. 4, pp. 198–201, 2005.

[49] T. Yang and W.A. Davis, "Planar half-disk antenna structures for ultra-wideband communications," in *Proc. IEEE Int. Symp. Antennas Propagation*, Monterey, CA, June 2004, vol. 3, pp. 2508–2511.

[50] Y. Zhang, Z.N. Chen, and M.Y.W. Chia, "Effects of finite ground plane and dielectric substrate on planar dipoles for UWB applications," in *Proc. IEEE Int. Symp. Antennas Propagation*, Monterey, CA, June 2004, pp. 2512–2515.

[51] D.H. Kwon and Y. Kim, "CPW-fed planar ultra-wideband antenna with hexagonal radiating elements," in *Proc. IEEE Int. Symp. Antennas Propagation*, Monterey, CA, June 2004, vol. 3, pp. 2947–2950.

[52] T.G. Ma and S.K. Jeng, "Planar miniature tapered-slot-fed annular slot antennas for ultrawide-band radios," *IEEE Trans. Antennas Propagat.*, vol. 53, no. 3, pp. 1194–1202, Mar. 2005.

[53] C.Y. Huang and W.C. Hsia, "Planar elliptical antenna for ultra-wideband communications," *Electron. Lett.*, vol. 41, no. 6, pp. 296–297, Mar. 2005.

[54] K. Al-Badwaihy and J. Yen, "Hemispherically capped thick cylindrical monopole with a conical feed section," *IEEE Trans. Antennas Propagat.*, vol. 22, no. 3, pp. 477–481, May 1974.

[55] H. Kawakami and G. Sato, "Broadband characteristics of rotationally symmetric antennas and thin wire constructs," *IEEE Trans. Antennas Propagat.*, vol. AP-35, pp. 26–32, Jan. 1987.

[56] W. Huang, A.W. Glisson, and A.A. Kishk, "Electromagnetic characteristics of a thick monopole antenna with dielectric loading,"in *Proc. IEEE Southeastcon*, Birmingham, AL, Apr. 12–15, 1992, no. 1, pp. 314–317.

[57] K.A. Wagner and S.S. Gearhart, "A novel impedance-tuned monopole antenna," *IEEE Int. Symp. Antennas Propagat.*, Montreal, Canada, July 1997, vol. 2, pp. 1332–1335.

[58] Z.N. Chen, "Broadband roll monopole," *IEEE Trans. Antennas Propagat.*, vol. 51, no. 11, pp. 3175–3177, Nov. 2003.

[59] Z.N. Chen, M.Y.W. Chia, and M.J. Ammann, "Optimization and comparison of broadband monopoles," *Proc. Inst. Elect. Eng. Microw. Antennas Propagat.*, vol. 150, no. 6, pp. 429–435, Dec. 2003.

[60] Z.N. Chen, "A new bi-arm roll antenna for UWB applications," *IEEE Trans. Antennas Propagat.*, vol. 53, no. 2, pp. 672–677, Feb. 2005.

[61] A. Koksal and F. Kauffman, "Moment method analysis of linearly tapered slot antennas," in *Proc. IEEE Int. Symp. Antennas Propagation.*, Ontario, Canada, vol. 1, June 1991, pp. 314–317.

[62] H.Y. Wang, D. Mirshekar-Syahkal, and I.J. Dilworth, "Numerical modeling of V-shaped linearly tapered slot antennas," in *Proc. IEEE Int. Symp. Antennas Propagation*, Montreal, Canada, July 1997, vol. 2, pp. 1118–1121.

[63] R.N. Simons and R.Q. Lee, "Linearly tapered slot antenna radiation characteristics at millimeter-wave frequencies," in *Proc. IEEE Int. Symp. Antennas Propagation*, Atlanta, GA, June 1998, vol. 2, pp. 1168–1171.

[64] J.B. Muldavin and G.M. Rebeiz, "Millimeter-wave tapered-slot antennas on synthesized low permittivity substrates," *IEEE Trans. Antennas Propagat.*, vol. 47, no. 8, pp. 1276–1280, Aug. 1999.

[65] M.F. Catedra, J.A. Alcaraz, and J.C. Arredondo, "Analysis of arrays of Vivaldi and LTSA antennas," in *Proc. IEEE Int. Symp. Antennas Propagation*, San Jose, CA, June 1989, vol. 1, pp. 122–125.

[66] E. Gazit, "Improved design of the Vivaldi antenna," *Proc. Inst. Elect. Eng., Microw. Antennas, Propagat.*, vol. 135, no. 2, pp. 89–92, Apr. 1988.

[67] J.D.S. Langley, P.S. Hall, and P. Newham, "Multi-octave phased array for circuit integration using balanced antipodal Vivaldi antenna elements," in *Proc. IEEE Int. Symp. Antennas Propagation*, vol. 1, pp. 178–181, .

[68] S.G. Kim and K. Chang, "Ultra wideband exponentially-tapered antipodal Vivaldi antennas," in *Proc. IEEE Int. Symp. Antennas Propagation*, Newport, CA, June 1995, vol. 3, pp. 2273–2276.

[69] X.M. Qing and Z.N. Chen, "Antipodal Vivaldi antenna for UWB applications," in *Proc. Euro Electromag.-UWB SP7*, Magdeburg, Germany, July 12–16, 2004.

[70] A. Cai, T.S.P. See, and Z.N. Chen, "Study of human head effects on UWB antenna," in *Proc. IEEE Intl. Workshop on Antenna Technology*, Singapore, 2005, pp. 310–313.

[71] Z.N. Chen, A. Cai, T.S.P. See, X.M. Qing, and M.Y.W. Chia, "Small planar UWB antennas in proximity of the human head," *IEEE Trans. Microwave Theory Tech.*, vol. 54, no. 4, pp. 1846–1857, 2006.

[72] K. Siwiak and D. McKeown, *Ultra-Wideband Radio Technology*. West Sussex, UK: Wiley, 2004.

[73] I. Oppermann, M. Hämäläinen, and J. Iinatti, *UWB: Theory and Applications*. West Sussex, UK: Wiley, 2005.

[74] H. Schantz, *The Art and Science of Ultra-Wideband Antennas*. West Sussex, UK: Artech House, 2005.

[75] B. Allen, M. Dohler, E. Okon, W. Malik, A. Brown, D. Edwards, *Ultra Wideband Antennas and Propagation for Communications, Radar and Imaging*. West Sussex, UK: Wiley, 2006.