Ultra Wideband Antennas – Past and Present

Eng Gee Lim, Zhao Wang, Chi-Un Lei, Yuanzhe Wang, K.L. Man

***Abstract*- Since the release by the Federal Communications Commission (FCC) of a bandwidth of 7.5GHz (from 3.1GHz to 10.6GHz) for ultra wideband (UWB) wireless communications, UWB is rapidly advancing as a high data rate wireless communication technology. As is the case in conventional wireless communication systems, an antenna also plays a very crucial role in UWB systems. However, there are more challenges in designing a UWB antenna than a narrow band one. A suitable UWB antenna should be capable of operating over an ultra wide bandwidth as allocated by the FCC. At the same time, satisfactory radiation properties over the entire frequency range are also necessary. This paper focuses on UWB planar printed circuit board (PCB) antenna design and analysis. Studies have been undertaken covering the areas of UWB fundamentals and antenna theory. Extensive investigations were also carried out on the development of UWB antennas from the past to present. First, the planar PCB antenna designs for UWB system is introduced and described. Next, the special design considerations for UWB antennas are summarized. State-of-the-art UWB antennas are also reviewed. Finally, a new concept for the design of a UWB antenna with a bandwidth ranging from 2GHz-11.3GHz is introduced, which satisfies the system requirements for S-DMB, WiBro, WLAN, CMMB and the entire UWB .**

Keywords*- *Ultra wideband, planar PCB Antenna and bandwidth.

I. INTRODUCTION

In February 14, 2002, the Federal Communications Commission (FCC) amended the Part 15 rules which govern unlicensed radio devices to include the operation of UWB devices. The FCC also allocated a bandwidth of 7.5GHz, i.e. from 3.1GHz to 10.6GHz to UWB applications [1], by far the largest spectrum allocation for unlicensed use the FCC has ever granted.

Ultra-wideband (UWB), a radio transmission technology which occupies an extremely wide bandwidth exceeding the minimum of 500MHz or at least 20% of the centre frequency [1], is a revolutionary approach for short-range high-bandwidth wireless communication. Differing from traditional narrow band radio systems (with a bandwidth usually less than 10% of the centre frequency) transmitting signals by modulating the amplitude, frequency or phase of the sinusoidal waveforms, UWB systems transmit information by generating radio energy at specific time instants in the form of very short pulses thus occupying very large bandwidth and enabling time modulation.

Due to the transmission of non-successive and very short pulses, UWB radio propagation will provide very high data rate which may be up to several hundred Megabytes per second, and it is difficult to track the transmitting data, which highly ensures the data security. For the same reason, the transmitting power consumption of UWB systems is extremely low in comparison with that of traditional narrow band radio systems. Moreover, the short pulses give rise to avoidance of multipath fading since the reflected signals do not overlap the original ones. Because of these alluring properties, UWB technology is widely employed in many applications such as indoor positioning, radar/medical imaging and target sensor data collection.

One of the challenges for the implementation of UWB systems is the development of a suitable or optimal antenna. The first important requirement for designing an UWB antenna is the extremely wide impedance bandwidth. In 2002, the US FCC allocated an unlicensed band from 3.1GHz to 10.6GHz on the frequency spectrum for UWB applications [1]. Hence, up to 7.5GHz of bandwidth is required for a workable UWB antenna. And commonly, the return loss for the entire ultra-wide band should be in the criterion of less than -10dB. Next, for indoor wireless communication, omnidirectional property in radiation pattern is demanded for UWB antenna to enable convenience in communication between transmitters and receivers. Therefore, low directivity is desired and the gain should be as uniform as possible for different directions.

Another important requirement is the radiation efficiency. Since the power transmitted into space is very low, the radiation efficiency is required to be quite high (normally the radiation efficiency should be no less than 70%). Moreover, linear phase in time domain characteristics is desired for UWB application. Since linear phase will produce constant group delay, the transmitted signals, in the form of extremely short pulses, will not be distorted and hence the system works effectively. Last but not least, since UWB technology is mainly employed for indoor and portable devices, the size of the UWB antennas is required to be sufficiently small so that they can be easily integrated into various equipments.

This paper focuses on UWB planar printed circuit board (PCB) antenna design and analysis. Extensive investigations are carried out on the development of UWB antennas from the past to present. First, the planar PCB antenna designs for UWB system is introduced and described. Next, the special design considerations for UWB antennas are summarized. State-of-the-art UWB antennas are also reviewed. Finally, a new concept (case studies) for the design of a UWB antenna with a bandwidth ranging from 2GHz-11.3GHz is

---

Eng Gee Lim is with the Xi'an Jiaotong-Liverpool University, 111 Ren'ai Road, Suzhou, Jiangsu 215123, China (tel: +86 512 8816 1405; fax: +86 512 8816 1999; e-mail: enggee.lim@xjtlu.edu.cn).

Zhao Wang is with the Xi'an Jiaotong-Liverpool University, 111 Ren'ai Road, Suzhou, Jiangsu 215123, China (e-mail: zhao.wang01@xjtlu.edu.cn).

Chi-Un Lei is with The University of Hong Kong, Pokfulam, Hong Kong (e-mail: culei@eee..hku.hk).

Yuanzhe Wang is with The University of Hong Kong, Pokfulam, Hong Kong (e-mail: yzwang@eee.hku.hk).

K.L.Man is with the Xi'an Jiaotong-Liverpool University, 111 Ren'ai Road, Suzhou, Jiangsu 215123, China (e-mail: ka.man@xjtlu.edu.cn).

introduced, which satisfies the system requirements for S-DMB, WiBro, WLAN, CMMB and the entire UWB with $S_{1,1} < -10$dB.

II. PLANAR PCB ANTENNA DESIGNS

As shown in Fig. 1 and 2, TEM horn antenna (Fig. 1.(a)), crossed and rolled monopole antennas (Fig. 1.(b)-(c)), modified rectangular/elliptical/slotted planar antennas (Fig. 2.(a)-(i)) are capable of yielding ultra wide bandwidth with nearly omni-directional radiation patterns [2-19]. However, those types of antenna are not a fully planar structure and the antenna size can not be significantly miniaturized in compared with full planar structure. Those antennas structure are also not suitable for integration with a PCB and hence limits their practical application. Therefore there is great demand for UWB antennas that offer fully planar structure.

In the design of a planar printed UWB antenna, the radiator is usually constructed and etched onto the dielectric substrate of a piece of the PCB and a ground plane near the radiator. The antenna can be fed by a microstrip transmission line or a coplanar waveguide (CPW) structure, as shown in Fig. 3.

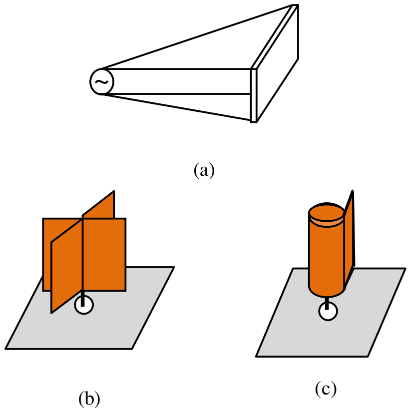

(a)
(b)
(c)

Figure 1. (a) TEM horn, (b) Crossed and (c) Rolled Antennas

Fig. 3(a) shows a typical planar printed monopole antenna fed by a microstrip transmission line [20]. This UWB antenna has a structure similar to the microstrip patch antenna, it consists of three layers: the top is a radiator; the middle is a substrate with dielectric constant; the bottom is an etched ground plane. This type of antenna can easily be integrated into system circuits for a compact design and fabricated at a very low manufacturing cost.

The geometry for the radiator of the planar PCB antenna may be elliptical, rectangular, triangular, or some combination or modified version from these regular geometries, as shown in Fig. 3(b)-(e) [21-24]. These antennas are optimized to cover UWB Bandwidth and to miniaturize the antenna size.

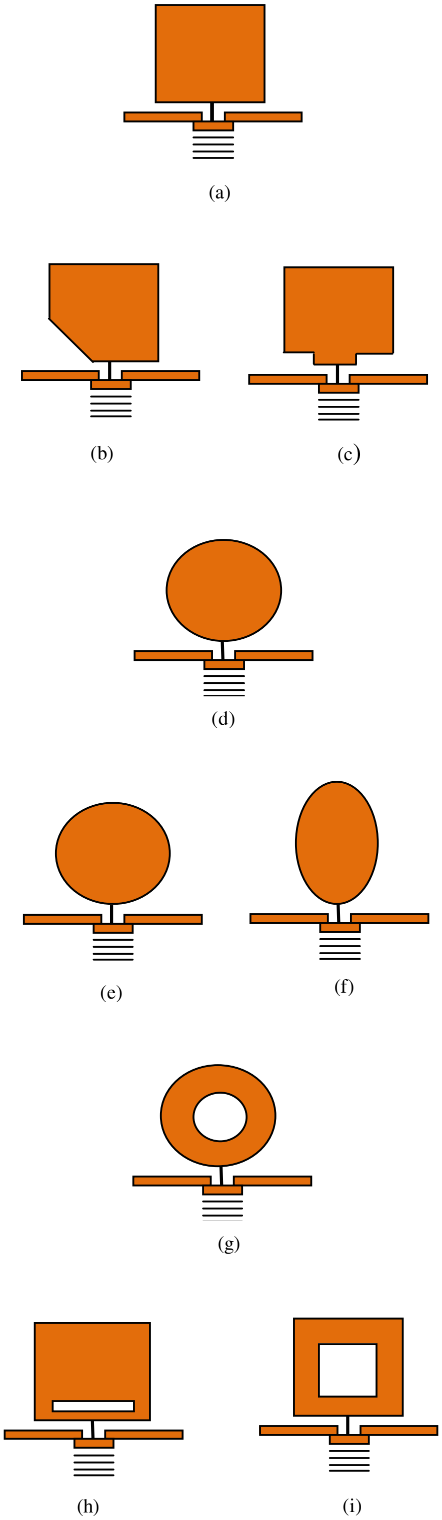

(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)

Figure 2. Modified Shapes Planar Antennas

In Fig. 3(b), in order to maximize the impedance bandwidth a pair of notches is placed at the two lower corners of the radiator and notch structure is also embedded in the truncated ground plane [21]. This phenomenon occurs because the two notches affect the electromagnetic coupling between the radiator and the ground plane. Moreover, the modified truncated ground plane acts as an impedance matching element to control the impedance bandwidth of a square monopole. Furthermore, the impedance matching can also be enhanced by modifying CPW-fed trapezoidal radiating patch with a PI-shaped matching stub or notching the radiator with a slit as shown in Fig. 3(c)-(d) [22-23].

In addition, the typical planar printed antenna consisting of a planar radiator and system ground plane is essentially unbalanced design, where the electric currents are distributed on both the radiator and the ground plane so that the radiation from the ground plane is inevitable. In order to reduce ground-plane effect for the UWB application, the design in Fig. 3(e) is being proposed [24]. In Fig. 3(e), the ground plane effect on the impedance performance is greatly reduced by removing the notch from the radiator because the electric currents on the ground plane are significantly suppressed at the lower edge operating frequencies. Such a characteristic are conductive to applications of the antennas in mobile devices. With the notch and additional attached strip, the overall size of the antenna can also be reduced for acceptable radiation efficiency.

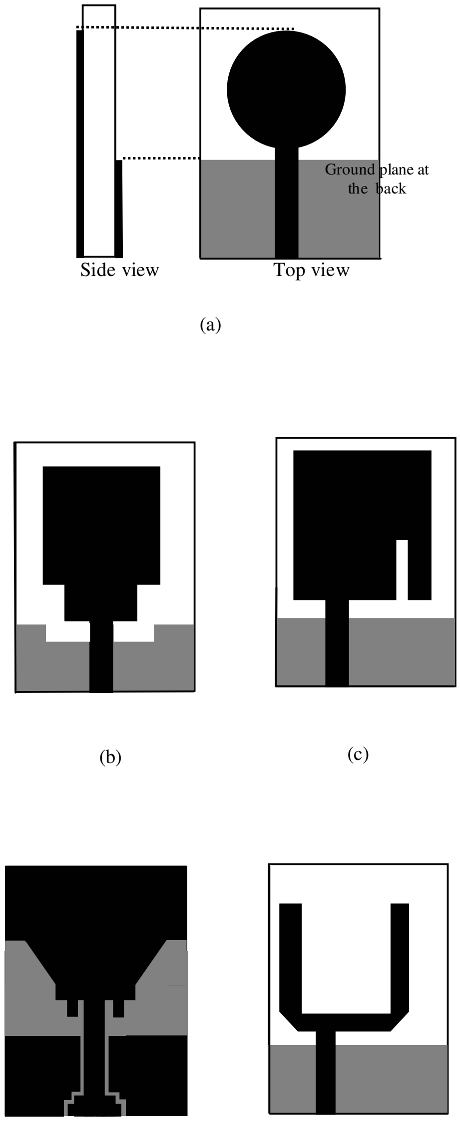
III. SPECIAL DESIGN CONSIDERATIONS FOR UWB ANTENNAS

Interference is a serious problem for UWB application systems. UWB applications are necessary for the rejection of the interference with existing wireless local area network (WLAN) technologies such as IEEE 802.11a in the USA (5.15-5.35GHz, 5.725-5.825GHz) [25]. As a result, UWB transmitters can not cause any electro-magnetic interference on nearby communication systems such as Wireless LAN (WLAN) applications. However, the use of a filter will increase the complexity of the UWB system.

Up to date, many UWB antennas have been attempted to overcome interference problem using frequency band rejected function design. In these designations, the filter can be eliminated and the radio frequency systems will be simplified. The most popular antennas design with frequency band rejected function approaches are embedding slots(arc-slot) [26], double U-slots [27], square-slot [28], V-slot [29], and attaching bar [29] as shown in Fig. 4(a)-(e).

Most of the designs in Fig. 3 have only single band-notched characteristic because the antennas with frequency band rejected function design occupy a large space of the antenna. Furthermore, some designs occupy too much wide band-notch that reaches more than 2GHz. However, the needed band-notches are 0.2GHz for lower WLAN band and 0.1GHz for upper WLAN band. The other designs can reject only one lower WLAN band or one upper WLAN band. Obtaining high efficiency band-notched characteristic is a challenging issue because it is very difficult to control the width of the band-notch in a limited space and the strong couplings between two band-notched characteristic designs for adjacent frequencies are obstacles to achieving efficient dual band-notched UWB antenna. Therefore, an efficient frequency band rejected technique for lower WLAN band and upper WLAN band is very difficult to implement.

Recently, the two separated strips on the radiator as shown in Fig. 5 has been proposed to control for the width of the band-notches and the rejected frequency[30]. The design in [30] provides very good band-notch for the lower WLAN (5.15-5.35GHz) band and the upper WLAN (5.725-5.825GHz) band.



(a)

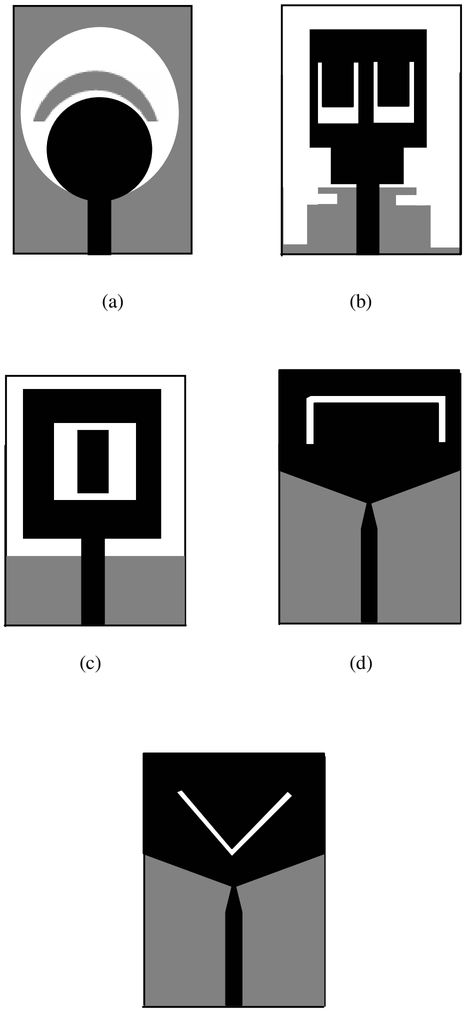
(b)

(c)

(d)

(e)

Figure 3. Planar PCB Antenna Designs



(a) (b)

(c) (d)

(e)

Figure 4. Antennas design with frequency band rejected function

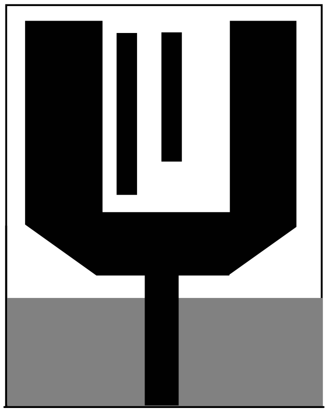


Figure 5. Dual Band-notched UWB Antenna

IV. CASE STUDY

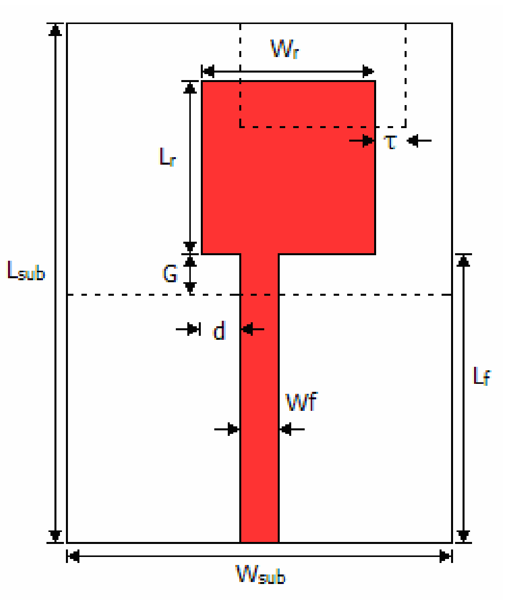
A. Design, Investigation and Optimization of a Compact UWB Antenna

As mentioned above, UWB technology has gained great popularity in research and industrial areas due to its high data rate wireless communication capability for various applications. As a crucial part of the UWB system, UWB antennas have been investigated a lot by researchers and quite a few proposals for UWB antenna design have been reported [2-24, 31-32]. However, the design of those proposed papers are quite complex and tolerance of those special features/variables on the antenna design will be a big issue when it goes to mass production. Hence, this has motivated us to design up a very low complexity, low cost and compact antenna to cover a very wide frequency band including Satellite Digital Multimedia Broadcasting (S-DMB), Wireless Broadband (WiBro), Wireless Local Area Network (WLAN), China Multimedia Mobile Broadcasting (CMMB) and the entire UWB.

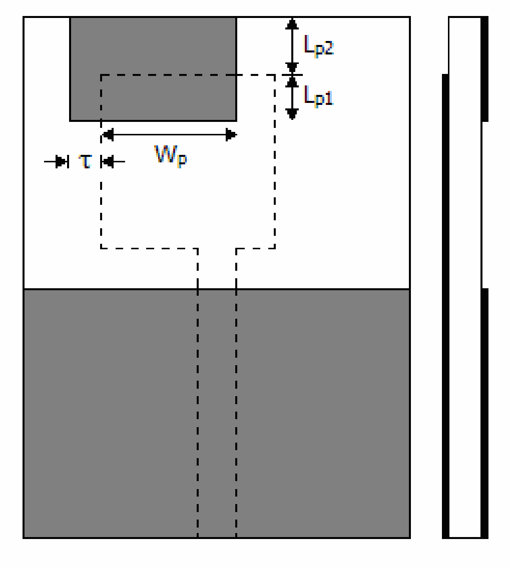
In this case study, we present a very simple rectangular (no perturbation) planar antenna having the operating bandwidth ranging from 2GHz-11.3GHz, by integrating various technologies into one compact antenna. We start with a simple rectangular planar antenna fed by a 50Ω microstrip line with a truncated ground plane. Next, based on the study of the feeding position and current distribution, the antenna is designed to have the operating bandwidth covering the entire UWB, i.e. 3.1GHz-10.6GHz. Then, studies upon the size of the partial ground plane are done to increase the bandwidth towards the lower side of the frequency spectrum, covering the bands for WLAN (2.4GHz-2.484GHz) and CMMB (2.635GHz–2.66GHz). With an extra patch printed on the back side of the substrate, underneath the rectangular radiator, the bandwidth can be further increased to cover Wibro (2.3GHz-2.4GHz) and S-DBM (2.17GHz-2.2GHz) without significantly influencing other frequency bands. Thus the proposed antenna can be applied in various applications: S-DBM, Wibro, WLAN, CMMB and the entire UWB. The operating bands are evaluated by CST Microwave Studio ™ 2009 [33] with the criterion of return loss $S_{1,1}$ less than -10dB. Simulated radiation patterns over the whole frequency bands are acceptable.

B. Antenna Configuration and Design

Fig. 6 shows the top, bottom and side views of the proposed antenna as well as its dimensions. As has been stated before, the antenna structure comes from a conventional design: a simple pure rectangular planar monopole antenna. L_r and W_r are critical parameters associated with the operating frequencies and input impedance of the antenna. Accordingly, L_r is selected to have a reasonable return loss at f_{middle} = 6GHz, which is approximate centre of the UWB band. A good starting point



(a) Top View



(b) Bottom view; *(c) Side view*

Figure 6. Configuration of the proposed antenna

for the dimension is as follows:

$$L_r \cong \frac{\lambda_{eff}\,, f_{\text{middle}}}{2} \tag{1}$$

where $\lambda_{eff} = \lambda_0 / \sqrt{\varepsilon_{eff}}$ is the effective wavelength for the radiation mode in the substrate with the effective dielectric constant. W_r is chosen to obtain reasonable return loss for the whole frequency band.

After performing the optimization of L_r and W_r, the radiator is having a small size of 13.8mm x 16mm$(L_r \text{ x } W_r)$ and printed on the top side of the 70mm x 60mm$(L_{sub} \text{ x } W_{sub})$ RT/Duriod 5870 substrate with dielectric constant $\varepsilon_r = 2.33$ and height $h = 0.79mm$.

In order to fulfil the requirements of a portable device, a microstrip feed line has been chosen for antenna feeding network. The following synthesis equations help determine the microstrip line [34]:

For

$$W_{eff} / h \geq 2$$

$$W_{eff} = \frac{2h}{\pi} \left\{ \begin{array}{l} \dfrac{\varepsilon_r - 1}{2\varepsilon_r} [\ln(B-1) + 0.39 - 0.61/\varepsilon_r] \\ +B - 1 - \ln(2B-1) \end{array} \right\} \tag{2}$$

For

$$W_{eff} / h \leq 2$$

$$W_{eff} = 8he^{A} / (e^{2A} - 2) \tag{3}$$

$$W_f = W_{eff} - \frac{t}{\pi}\left[1 + \ln(2h/t)\right] \tag{4}$$

where W_{eff} and W_f are the effective and physical widths of the microstrip line, h and t are the thickness of the substrate and patch.

$$A = \frac{Z_{ol}}{60}\left(\frac{\varepsilon_r + 1}{2}\right)^{0.5} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}(0.23 + 0.11/\varepsilon_r)$$

$$B = \frac{377\pi}{2Z_{ol}\sqrt{\varepsilon_r}}$$

These equations provide a starting point of a 50Ω microstrip line width -- 2.36mm.

C. Parametric Studies and Simulation Results

The simulated results are evaluated by CST Microwave Studio 2009 [33] and modeled by Vector Fitting [37] for ease of simulation.

C.1. Learning the feeding position

As has been stated before, the feeding position has been studied. Fig. 7 gives the return loss of the antenna due to different feeding positions. It can be seen that the operating bandwidth is sensitive to the offset of the radiator and when the radiator shifts 2.5mm away from the symmetrical position, the resulting bandwidth is from 3GHz to 11GHz, covering the entire UWB band.

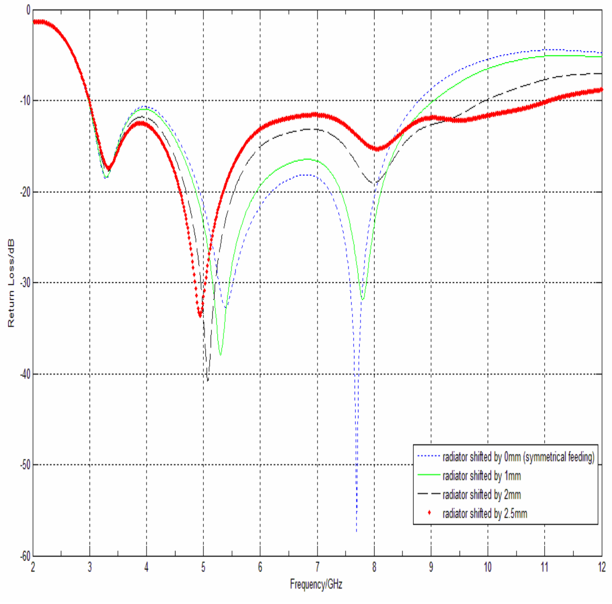


Figure 7. Return loss due to different feeding positions

It is worth noticing that the impedance matching is very sensitive to the dimensions of the antenna. For different stages, the antenna dimensions should be slightly re-optimized to achieve impedance matching purpose.

C.2. Studying the size of the truncated ground plane

Fig. 8 gives the return loss of the antenna due to different lengths of the ground plane. Again, at this stage, to meet the impedance matching, the antenna dimension is slightly adjusted. It can be seen that the lower side of operating bandwidth becomes even lower, following the increment in the length of the ground plane. When $L_f = 35mm$ and the radiator is optimized to $14.8mm \times 16mm$ $(L_r \times W_r)$, as seen from Fig. 8, the antenna is designed to cover 2.35GHz-11.2GHz, which is able to include CMMB and WLAN applications.

For space saving purpose, the substrate width W_{sub} is reduced to 50mm. At the same time, the radiator is modified to $16mm \times 16mm$ while the feed line width is optimized to 2.2mm for impedance matching purpose. Comparison with the unreduced-substrate design is made in Fig. 9. As the Fig. shows, when the width of the substrate is reduced, the impedance matching is significantly affected. This is due to the influence on current distribution, since for a UWB planar antenna, the electric current is greatly affected by the shape and size of the system ground plane [7, 8].

C.3. Investigating the additional patch

To cover more bands, a promising idea is to add an extra patch underneath the radiator, on the bottom side of the substrate (Fig. 6 (b)). Intensive work has been done to investigate the antenna performance due to different dimensions of the additional patch.

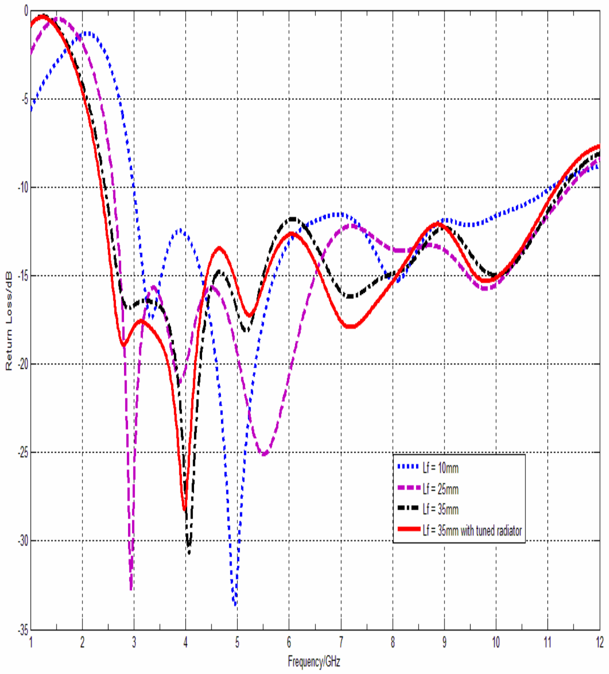


Figure 8. Return loss due to varying ground plane length

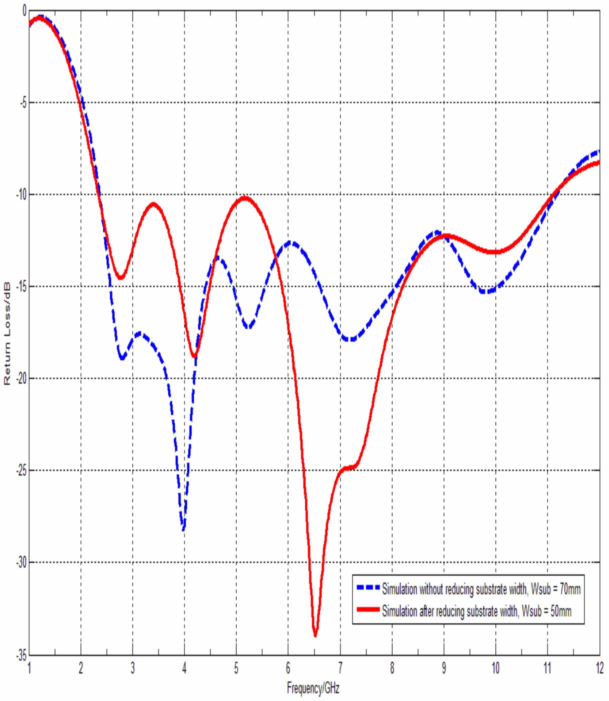


Figure 9. Return loss due to reduced substrate width

We set $L_{p1} = -0.8mm; L_{p2} = 2.8mm; W_p = 16mm; and \tau = 0mm$ as a starting point for our study. Then try to vary L_{p1} and see the differences in antenna performance. The return loss plots due to different values of L_{p1} are shown in Fig. 10. From the plots, it is found that increasing L_{p1} can help shift the frequency band to the lower side. It should be noticed that the bandwidth can hardly be affected by further increment in L_{p1} as long as it reaches 1mm. However, impedance matching is improved at lower frequencies due to larger L_{p1}.

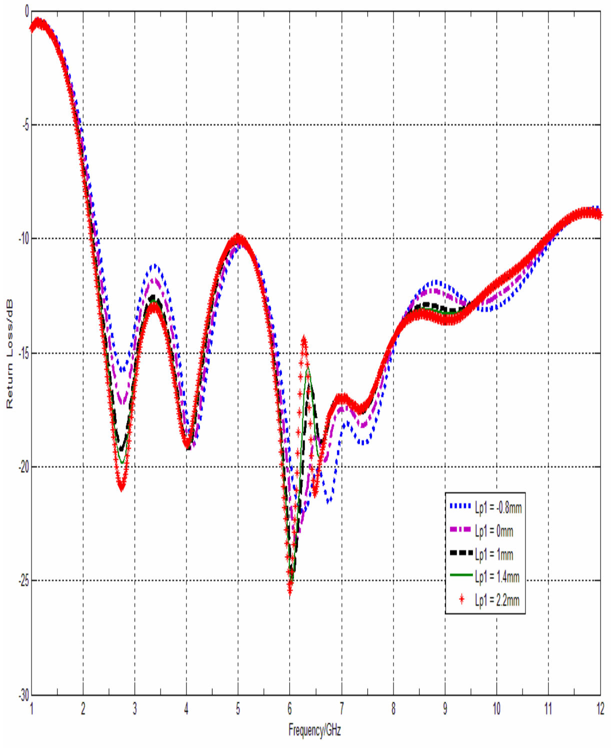


Figure 10. Parametric study on Lp1

Next, we hold $L_{p1} = 1.4mm; L_{p2} = 2.8mm$ and $\tau = 0mm$ and start to see how W_p can affect the performance. Changes in return loss due to the variation in W_p are concluded in Fig. 11. It is clear to see that W_p can affect the middle frequency band but hardly the lower and upper bands.

Next, we start to investigate how the extending part τ can influence the return loss. Based on the above findings, we start with $L_{p1} = 2.2mm; L_{p2} = 2.8mm$ and $W_p = 13mm$. The simulation results are put into Fig. 12. Again, it can be seen that the extending part τ can affect the impedance matching in the middle frequency band while presenting negligible influence on the lower and upper bands.

Based on the above results, the parameters are set as $L_{p1} = 2.2mm; W_p = 13mm$ and $\tau = 0mm$. Investigations are then made on L_{p2} to see whether the variation in L_{p2} can influence the antenna performance. Fig. 13 gives the simulation results. It is clear to see that larger L_{p2} helps move the lower operating bands towards even lower side of the frequency spectrum without influencing the upper bands, resulting in an ultra-wideband ranging from 2GHz-11.3GHz. Moreover, the impedance matching is greatly improved at lower frequencies

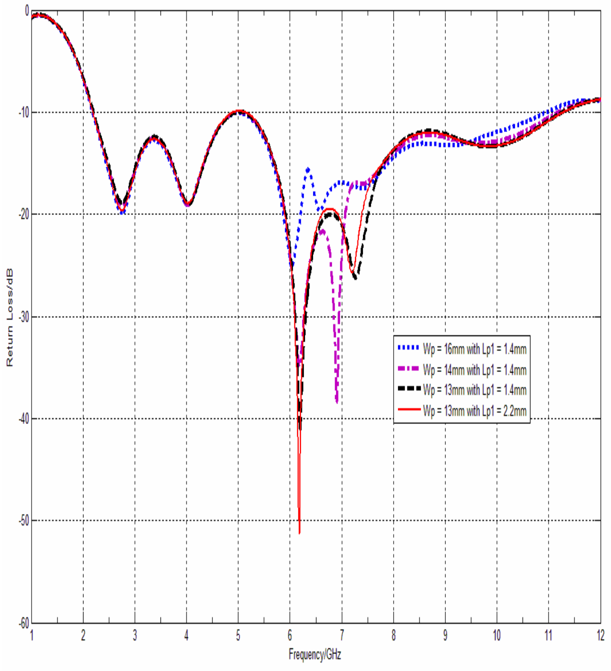


Figure 11. Parametric study on Wp

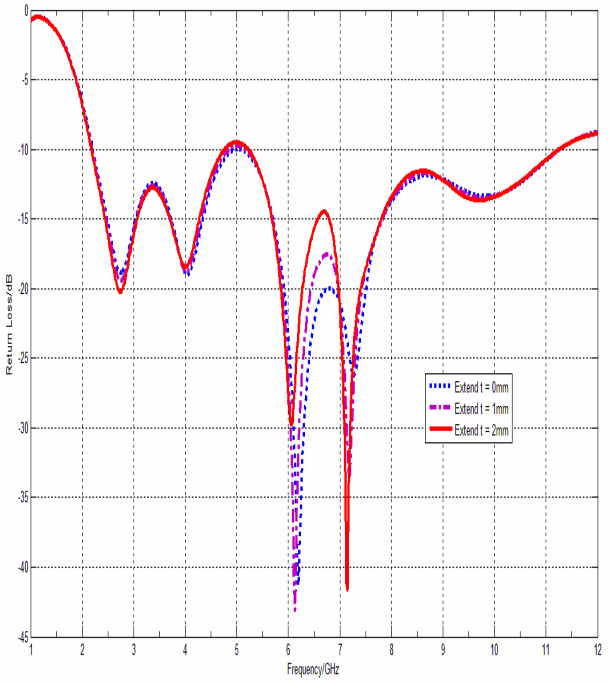


Figure 12. Parametric study on the extending part τ

.

Up to now, optimized dimensions for the extra-patch equipped UWB planar antenna are obtained:

$$W_{sub} \times L_{sub} = 50 \times 60mm^2; W_r \times L_r = 16 \times 16mm^2$$
$$L_f = 35mm; W_f = 2.2mm; G = 1.4mm; d = 4.4mm$$
$$L_{p1} = 2.2mm; L_{p2} = 10mm; W_p = 13mm; \tau = 0mm$$

Comparison between the optimized design and the one without the extra patch in terms of the return loss is given in Fig. 14

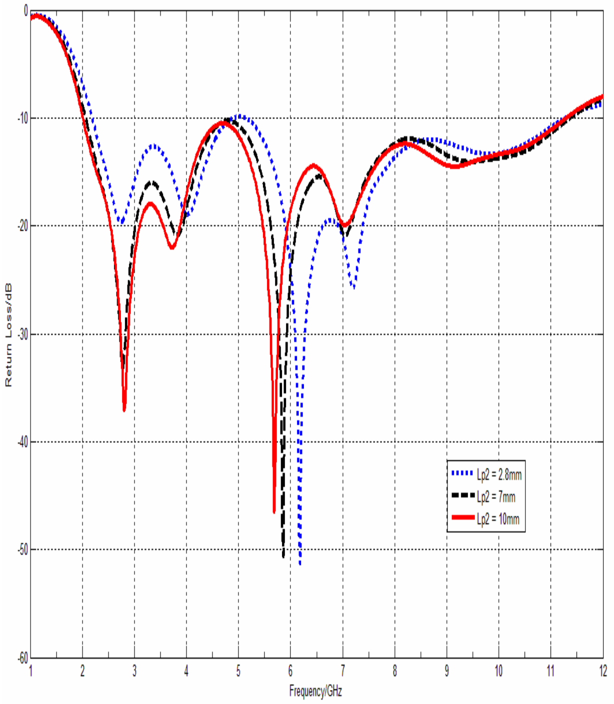


Figure 13. Parametric study on Lp2

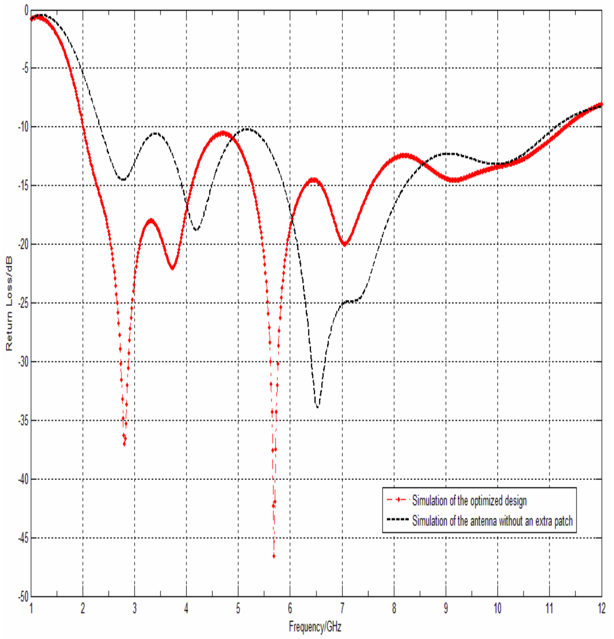


Figure 14. Comparison between optimized design and the one without the extra patch

The current distributions are evaluated to help understand the performance of the antenna. Fig. 15 and 16 illustrate the simulated current distributions on the antenna at 2.4GHz, 3.1Ghz, 7GHz and 10GHz. It is worth noticing that the current distribution has extended into the additional patch on the lower edge of the radiator and the patch, which contributes to the lower end of the operating band. Therefore the operating frequency is extended downwards to 2GHz for this design.

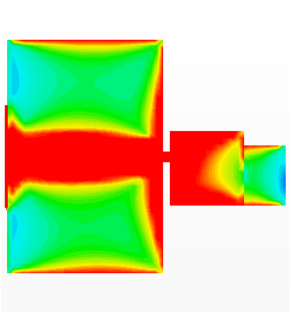
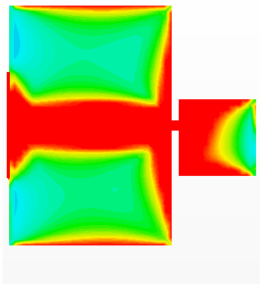
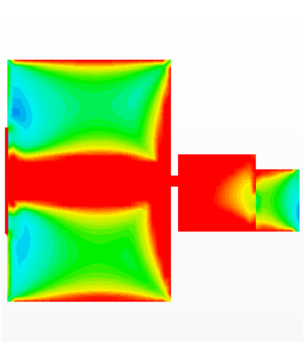
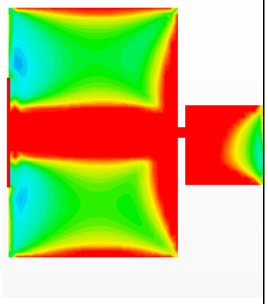
With the extra patch	Without the extra patch
	
(a) At 2.4GHz	
	
(b) At 3.1GHz	

Figure 15. Comparison between optimized design and the one without the extra patch at 2.4GHz and 3.1GHz

Simulations for radiation pattern have been performed at 2.4 GHz and 10GHz (see Fig. 17 and 18). The radiation pattern at y-z plane (E-plane) is in donut shape, and the x-y plane (H-plane) is omni-directional at lower frequencies, and shifted to -y direction which contributes more at higher frequency band

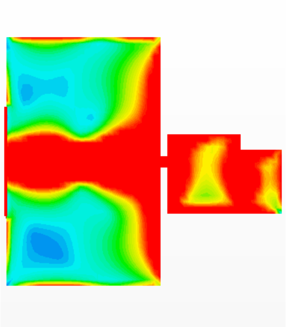
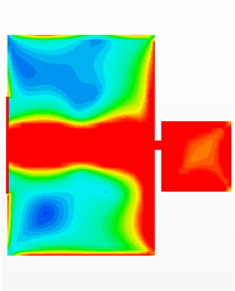
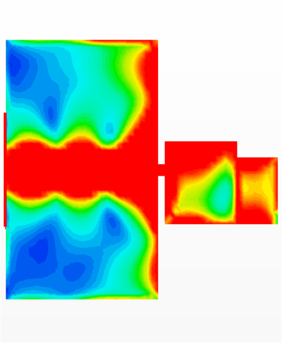
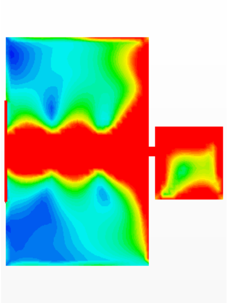
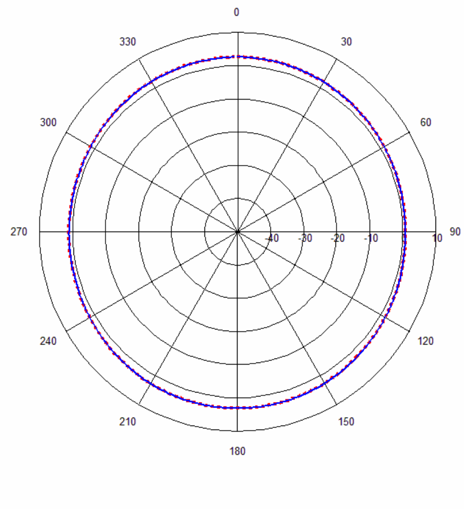
With the extra patch	Without the extra patch
	
(c) At 7GHz	
	
(d) At 10GHz	

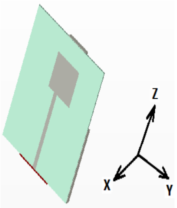
Figure 16. Comparison between optimized design and the one without the extra patch at 7GHz and 101GHz.

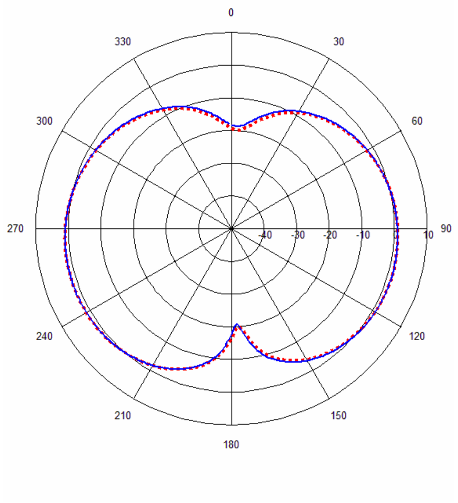
V. CONCLUSION

Since the release by the Federal Communications Commission (FCC) of a bandwidth of 7.5GHz (from 3.1GHz to 10.6GHz) for ultra wideband (UWB) wireless communications, UWB is rapidly advancing as a high data rate wireless communication technology. As is the case in conventional wireless communication systems, an antenna also plays a very crucial role in UWB systems. Therefore, UWB planar printed circuit board (PCB) antenna design and analysis have been discussed in this paper. Studies have been undertaken covering the areas of UWB fundamentals and antenna theory. Extensive investigations were also carried out on the development of UWB antennas from the



x-y plane

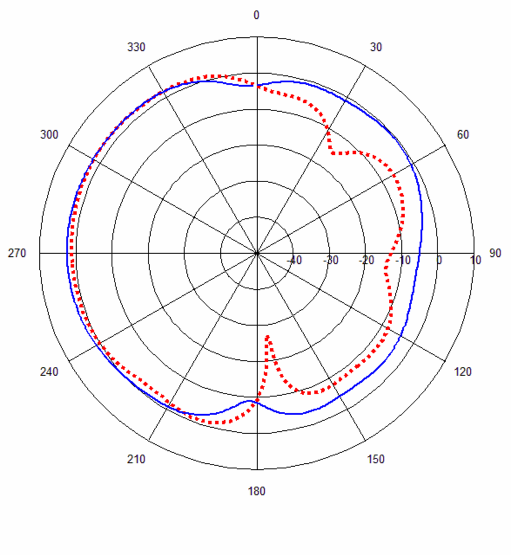




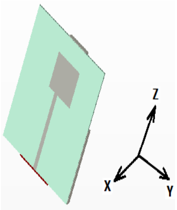
y-z plane

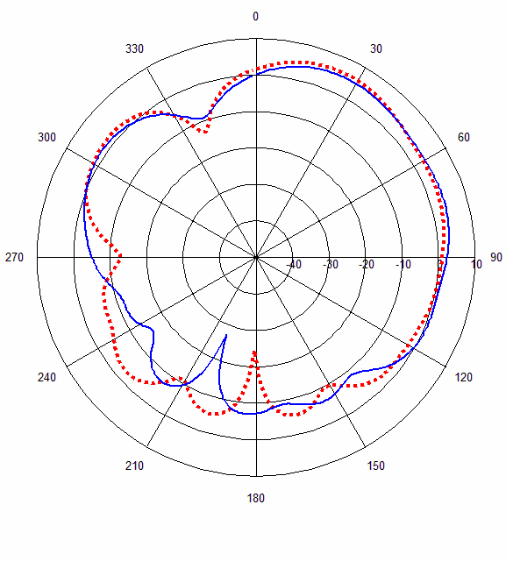
(a) At 2.4GHz

Figure 17. Comparisons of the radiation patterns at 2.4GHz (Dotted line: with extra patch; Solid line: without extra patch):



x-y plane





y-z plane

(b) At 10GHz

Figure 18. Comparisons of the radiation patterns at 10GHz (Dotted line: with extra patch; Solid line: without extra patch):

past to present. First, the planar PCB antenna designs for UWB system is introduced and described. Next, the special design considerations for UWB antennas were discussed and summarized. In addition, a state-of-the-art for the design of a UWB antenna with a bandwidth ranging from 2GHz-11.3GHz was presented, which satisfies the system requirements for S-DMB, WiBro, WLAN, CMMB and the entire UWB .

REFERENCES

[1] Federal Communications Commission, Washington, DC, “FCC report and order on ultra wideband technology”, 2002.

[2] L.T. Chang and W.D. Burnside, “An ultrawide-bandwidth tapered resistive TEM horn antenna”, *IEEE Transactions on Antennas and Propagation*, vol.48, 2000, pp.1848–1857.

[3] R.T. Lee and G.S. Smith, “On the characteristic impedance of the TEM horn antenna”, *IEEE Transactions on Antennas and Propagation*, vol.52, 2004, pp.315–318.

[4] M.J. Ammann, “Improved pattern stability for monopole antennas with ultrawideband impedance characteristics”, *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, vol.1, Jun 2003, pp. 818–821.

[5] Z.N. Chen, M.Y.W. Chia, and M.J. Ammann, “Optimization and comparison of broadband monopoles”, *IEE Proceedings – Microwaves, Antennas and Propagation*, vol.150, 2003, pp.429-435.

[6] Z.N. Chen, “A new bi-arm roll antenna for UWB applications”, *IEEE Transactions on Antennas and Propagation*, vol.53, 2005, pp.672–677.

[7] M.J. Ammann, “Impedance bandwidth of the square planar monopole”, *Microwave and Optical Technology Letters*, vol.24, 2000, pp.185–187.

[8] M.J. Ammann and Z.N. Chen, “An asymmetrical feed arrangement for improved impedance bandwidth of planar monopole antennas”, *Microwave and Optical Technology Letter*s, vol.40, 2004, pp.156–158.

[9] K.G. Thomas, N. Lenin, and R. Sivaramakrishnan, “Ultrawideband planar disc monopole”, *IEEE Transactions on Antennas and Propagation*, vol.54, 2006, pp.1339–1341.

[10] S. Su, K. Wong, and C. Tang, “Ultra-wideband square planar antenna for IEEE 802.16a operating in the 2–11GHz band”, *Microwave and Optical Technology Letters*, vol.42, 2004, pp.463–466.

[11] X.H. Wu and Z.N. Chen, “Comparison of planar dipoles in UWB applications”, *IEEE Transactions on Antennas and Propagation*, vol.53, 2005, pp.1973–1983.

[12] M.J. Ammann and Z.N. Chen, “A wideband shorted planar monopole with bevel”, *IEEE Transactions on Antennas and Propagation*, vol.51, 2003, pp.901–903.

[13] N.P. Agrawall, G. Kumar, and K.P. Ray, “Wide-band planar monopole antenna”, *IEEE Transactions on Antennas and Propagation*, vol.46, 1998, pp.294–295.

[14] C.Y. Huang and W.C. Hsia, “Planar elliptical antenna for ultra-wideband communications”, *Electronics Letters*, vol.41, 2005, pp.296–297.

[15] P.V. Anob, K.P. Ray, and G. Kumar, “Wideband orthogonal square monopole antennas with semi-circular base”, *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, vol. 3, July 2001, pp.294– 297.

[16] H.S. Choi, J.K. Park, S.K. Kim, and J.Y. Park, “A new ultra-wideband antenna for UWB applications”, *Microwave and Optical Technology Letters*, vol.40, 2004, pp.399–401.

[17] S.Y. Suh, W.L. Stutzman, and W.A. Davis, “A new ultrawideband printed monopole antenna: the planar inverted cone antenna (PICA)”, *IEEE Transactions on Antennas and Propagation*, vol.52, 2004, pp.1361–1364.

[18] Z.N. Chen, M.J. Ammann, M.Y.W. Chia, and T.S.P. See, “Circular annular planar monopoles with EM coupling”, *IEE Proceedings – Microwaves, Antennas and Propagation*, vol.150, 2003, pp.269–273.

[19] D. Valderas, J. Meléndez, and I. Sancho, “Some design criteria for UWB planar monopole antennas: Application to a slotted rectangular monopole”, *Microwave and Optical Technology Letters*, vol.46, 2005, pp.6–11.

[20] J.Clerk, J.Liang, C.C.Chiau, X.Chen and C.G.Parini, “Study of printed circular disc monopole antenna for UWB systems,” *IEEE Transaction on Antennas and Propagation*, vol.53, November 2005, pp.3500-3504.

[21] J.Jung, W.Choi, J.Choi, “A small wideband microstrip-fed monopole antenna”, *IEEE Microwave and Wireless Component Letters.* vol.15, Oct 2005, pp.703-705.

[22] K.Chung, H. Park, and J.Choi, “Wideband Microstrip-fed monopole antenna with a narrow slit”, *IEEE Microwave and Optical Technology Letters*, vol.47, 2005, pp.400-402.

[23] J.N.Lee, J.H.Yoo, J.H.Kim, J.K.Park, J.S.Kim, “A Novel UWB antenna Using PI-Shaped Matching Stub for UWB Applications”, *IEEE International Conference on Ultral-wideband (ICUWB2008)*, vol.1, 2008, pp.109-112.

[24] Z.N.Chen, T.S.P.See, X.Qing, “Small printed ultrawideband antenna with reduced ground plane effect”, *IEEE Transactions on Antennas and Propagation*, vol.53, Feb 2007, pp.383-388.

[25] FCC Website, www.fcc.gov/pshs/techtopics/techtopics10.html .

[26] A.A.Kalteh, R.Fallahi, and M.G.Roozbahani, “A novel Microstrip-fed UWB Circular slot antenna with 5-Ghz Band-notch characteristics”, *IEEE International Conference on Ultral-wideband (ICUWB2008)*, vol.1, 2008, pp.117-120.

[27] M.Ojaroudi, G.Ghanbari, N.Ojaroudi, C.Ghobadi, “Small square monopole antenna for UWB applications with Variable frequency band-notch function”, *IEEE Antennas and Wireless Propagation Letters*, vol.8, 2009.

[28] H.w.Liu, C.H.Ku, T.S.Wang, C.F.Yang, “Compact monopole antenna with band-notched characteristic for UWB applications”, *IEEE Antennas and Wireless Propagation Letters*, vol. 9, 2010.

[29] B.Ahamadi, R.F.Dana, “A miniaturized monopole antenna for ultra-wideband applications with band-notch filter”, *IET Microwave antennas Propagations*, vol.3, 2009, pp.1224-1231.

[30] K.S.Ryu, A. A. Kishk, “UWB antenna with single or dual band-notches for lower WLAN band and upper WLAN Band,” *IEEE Transactions on Antennas and Propagation*, vol.57, Dec 2009, pp.3942-3950.

[31] Seok H. Choi, Jong K. Park, et al, “A new ultra-wideband antenna for UWB applications”, *Microwave and Optical Technology Letters*, vol. 40, Mar 2004.

[32] Bahadir S. Yildirim, Bedri A. Cetiner, et al, “Integrated Bluetooth and UWB Antenna”, *IEEE antennas and wireless propagation letters*, vol. 8, 2009.

[33] CST Microwave Studio, version 2009,00.

[34] J.D. Woermbke, “Soft Substrates Conquer Hard Designs,” *Microwaves*, January, 1982, pp. 89-98.

[35] 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*, Jun 2004, pp.2512-2515.

[36] Z. N. Chen, N. Yang, Y. X. Guo, and M. Y. W. Chia, “An investigation into measurement of handset antennas”, *IEEE Transaction Instrumentation Measurement.*, vol. 54, Jun 2005, pp. 1100-1110

[37] C.U. Lei, Y. Wang, Q. Chen, N. Wong, "On Vector Fitting Methods in Signal/Power Integrity Applications", *Lecture Notes in Engineering and Computer Science: Proceedings of The International MultiConference of Engineers and Computer Scientists 2010*, IMECS 2010, 17-19 March, 2010, Hong Kong, pp.1407-1412