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Design of a CPW-fed Dual Band-Notched Planar Wideband Antenna for UWB Applications

Fei Yu and Chunhua Wang
Hunan University
People's Republic of China

1. Introduction

Since the first Report and Order by the Federal Communications Commission (FCC) authorized the unlicensed use of ultra wideband (UWB) which must meet the emission masks on February 14, 2002 [1], both industry and academia have paid much attention to R&D of commercial UWB systems. Among UWB system design, the UWB antenna is the key component. Recently, a considerable amount of researches have been devoted to the development of the UWB antenna for its enabling high data transmission rates, low power consumption and simple hardware configuration in communication applications such as radio frequency identification devices, sensor networks, radar, location tracking, etc. Nowadays, the planar printed antenna fed with a microstrip line or a coplanar waveguide (CPW) has received much attention due to its high radiation efficiency and compact size and can be easily integrated with the other circuit. However, compared to the microstrip-fed antennas, the CPW-fed antennas are very good candidates since the feed line and slots are on one side of the substrate [2]. In order to obtain ultra wideband, the different optimum metal radiation patch geometries have been developed, like fork shape [3], elliptical shape [4], square shape [5], spade shape [6], circle shape [7], or made some modifications about the radiation patch [8]. Besides, over the designated frequency band, there exist some narrow bands for other communication systems, such as WiMAX operating in the 3.3 to 3.6 GHz band, and WLAN operating in the 5.15 to 5.825 GHz. They may cause communication interference with the UWB system. To solve this problem, it is desirable to design antennas with band notched characteristics to minimise potential interference. Several UWB antennas with frequency band notched function have been reported recently. The reported antennas are generally embedded with a half-wavelength structure such as a ω -shaped slot [2], a U-shaped slot [4], a C-shaped slot [8], or a V-shaped slot [9]. But most reported antennas were designed with only one notched band, mainly discussed on WLAN frequency band 5.15 to 5.825 GHz. UWB antennas with dual notched band were recently reported. In [10], the dual notched bands were formed by two nested C-shaped slots embedded in the bevelled patch. A pair of asymmetrical spurlines on the feedline was used to achieve dual notched band in [11]. A recently reported antenna has been designed by making use of two split resonant rings (SRR) to obtain dual band-notched characteristics [12]. Nevertheless, the geometry of the SRR structure is relatively complex.

In this paper, a CPW-fed novel planar ultra-wideband antenna with dual band-notched characteristics is introduced. In order to obtain ultra wideband, some modifications about

the antenna are introduced. Simply by etching a U-shaped slot in the radiating element, single band-notched characteristic from 5 to 6 GHz can be easily obtained. By etching two nested U-shaped slots in the radiating patch, dual band-notched characteristics for the proposed UWB antenna can be created to reduce the potential interferences between UWB system and narrowband systems. Details of the antenna design and simulation are presented in order to demonstrate the performance of the proposed antennas. Sec. 2 presents the details of the antenna structure and the design procedure. The antennas with single and dual band-notched characteristics were designed in Sec. 3. Sec. 4 analyses the radiation patterns and makes a comparison between recently proposed antennas and this antenna. Finally, the conclusion is presented in Sec. 5.

2. UWB antenna design

It is well known that the rectangular patch antenna has a narrow-band characteristic. To improve its operating bandwidth, we shape the bottom of the patch into an arc. In practical applications, the size of ground plane is finite and the direction of maximum radiation tilts somewhat upwards from the horizontal plane. To reduce this beam tilting, the ground plane of the proposed antenna is designed to have not rectangular but rounded shape. The arc-shaped patch and tapered ground plane make good broadband impedance matching of the antenna possible. To further expand the impedance bandwidth, a right-angle triangle on the upper corners of the patch and a small fan angle on each side of the ground plane near the feeding line are removed respectively. The improvement process steps are shown in Fig. 1.

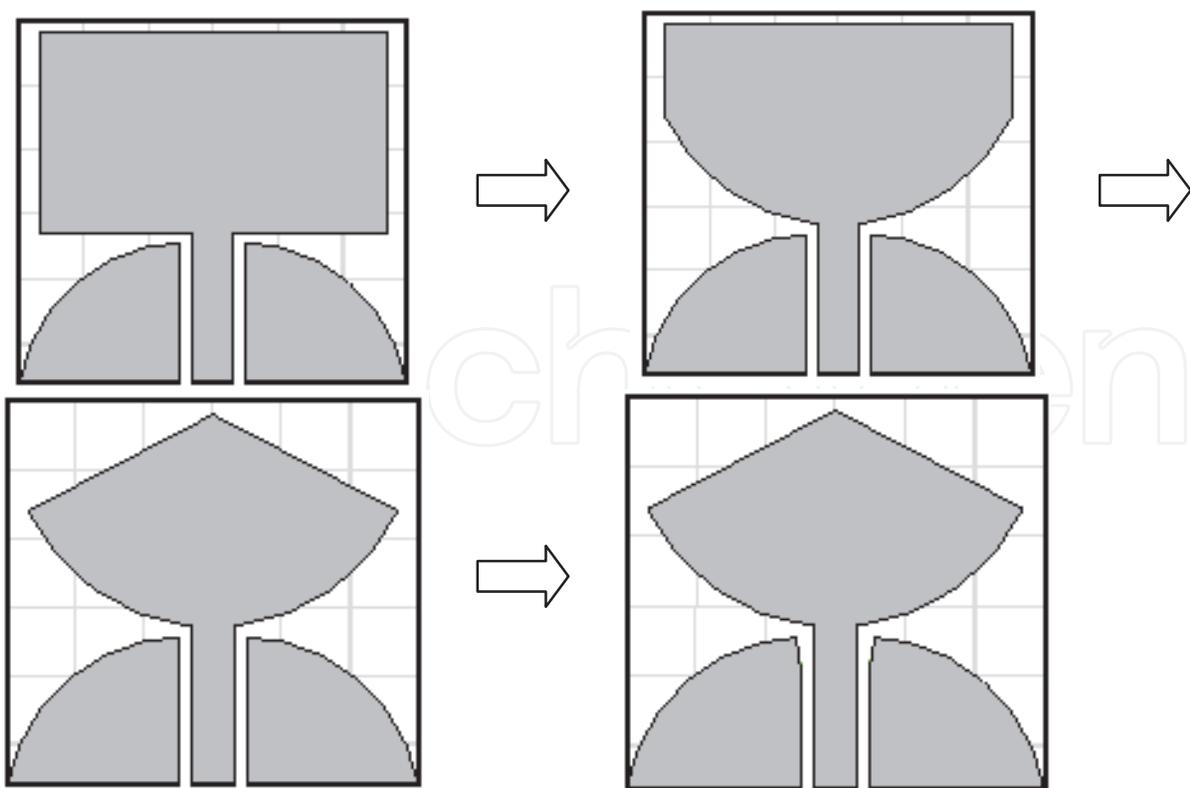


Fig. 1. The improvement process of the antenna

A comparison of the simulated reflection coefficient (S_{11}) of the antenna with a full rectangular radiating patch, with the modification of the bottom side, with the cuts on the upper corners, and with the small angle on each side of the ground plane is plotted in Fig. 2 when all the dimensions are the same. It can be seen that the first line demonstrates the rectangular patch antenna has a narrow-band characteristic. The second line shows the impedance bandwidth is broadened when the bottom of the patch is shaped into an arc. On the basis of this, the third line about the upper corners modification indicates the bandwidth is further expanded compared with the second line (the main advantages that this modification is reducing the lowest frequency). The fourth line demonstrates the small angle on each side of the ground plane near the feeding line will affect the characteristic impedance of the CPW line and also explains the proposed antenna has a very wide impedance bandwidth.

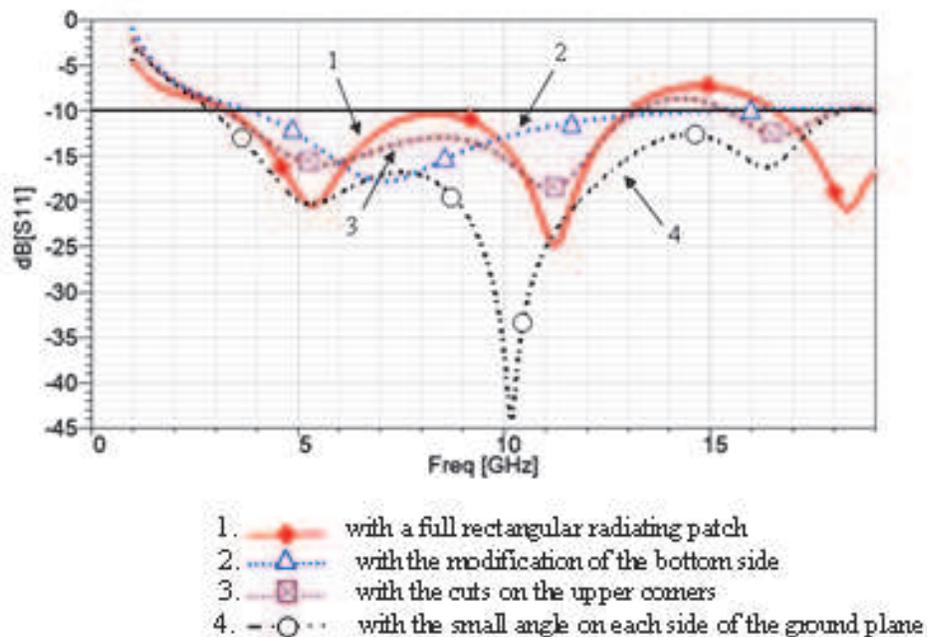


Fig. 2. Simulated reflection coefficient for different shapes of the radiation patch and the ground plane

The final geometry of the proposed compact band-notched antenna is depicted in Fig. 3. The antenna (referred to as antenna A) is printed on a FR4 substrate with size 28 mm × 30 mm, thickness of 1.6 mm, relative permittivity of 4.4 and loss tangent $\tan \delta = 0.02$. The proposed antenna is located in x-y plane and the normal direction is parallel to z-axis. The center strip and gap of the CPW line are 3.6 mm and 0.3 mm to achieve 50- Ω port characteristic impedance. By the improvement steps mentioned above the second paragraph, good impedance matching can be achieved across a wide bandwidth. We optimize the antenna geometrical parameters for $S_{11} < -10$ dB over the entire frequency range (3.1-10.6 GHz). The optimisation procedure is done by using Ansoft HFSS software. The final antenna geometry parameters are obtained as $L_1 = 28$ mm, $L_2 = 30$ mm, $L_3 = 13.5$ mm, $L_4 = 5$ mm, $L_5 = 1.5$ mm, $L_6 = 10.8$ mm, $L_7 = 5.4$ mm, $L_8 = 12.9$ mm, $R = 15$ mm, $g = 0.7$ mm, $f = 3.6$ mm, $c = 0.3$ mm, $t = 0.3$ mm, $H = 1.6$ mm. By selecting the optimal parameters, the proposed antenna can be tuned to operate within the UWB band.

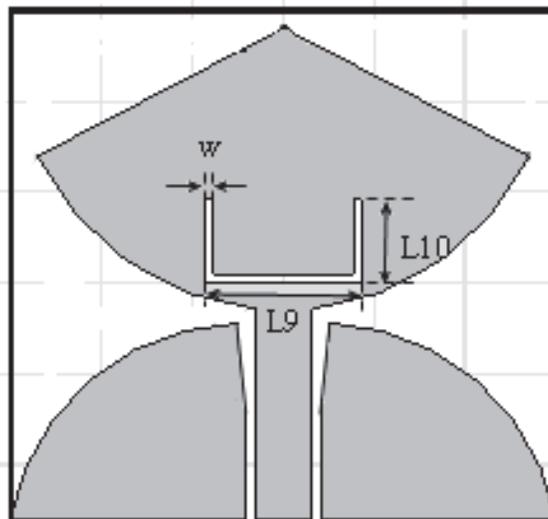


Fig. 4. Configuration of the proposed antenna B

design. From (1), we can know the length of the U-shaped slot ($L = L9 + 2L10$) is a crucial parameter to determine the center frequency of the stop band. In this design, the U-shaped slot was chosen to be nonresponsive close to about 0.33λ at the center frequency of the desired notched-band, where λ is the wavelength at the center frequency of the rejection band, the final design parameters of the U-shaped slot are $L9 = 8.6$ mm, $L10 = 4.6$ mm, $w = 0.2$ mm.

The impedance performance of the designed antenna was simulated using electromagnetic software Ansoft HFSS 11 which is based on finite element analysis. The simulated VSWR is shown in Fig. 5. The result demonstrates that a stop-band can be obtained by inserting a U-shaped slot in radiating patch. Compared to antenna A design, the single band-notched UWB antenna successfully blocks out the 5 to 6 GHz band and still performs good impedance-matching at other frequencies in the UWB band. Fig. 6 shows the simulated current distributions at specific frequencies. In Fig. 6(a) and (c), at frequencies 3.5 and 7.5 GHz, the current distributions mainly flow along the transmission line; while around the U-shaped slot the current is small. The simulated current distribution at 5.5 GHz is shown in

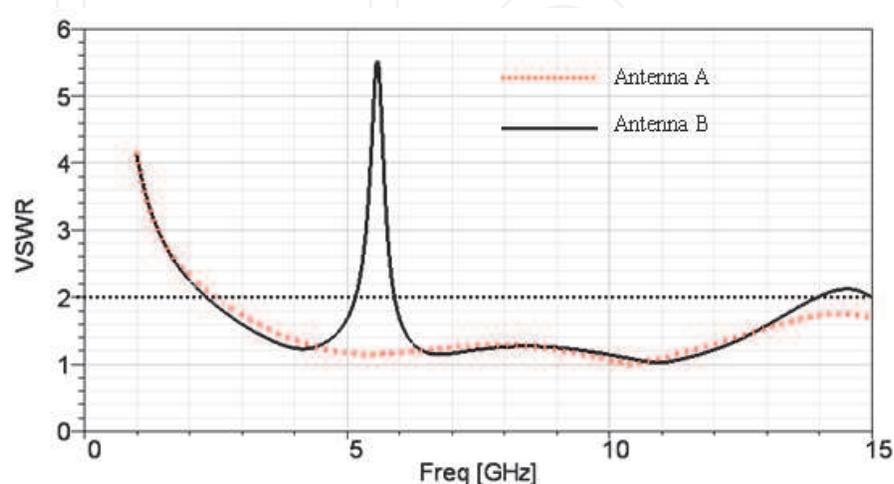
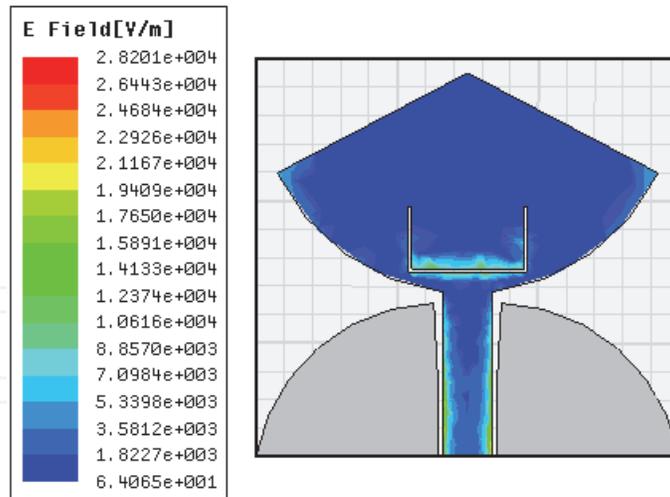
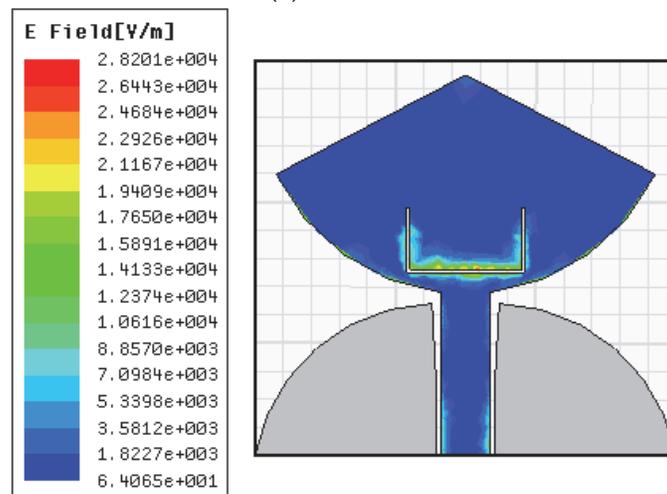


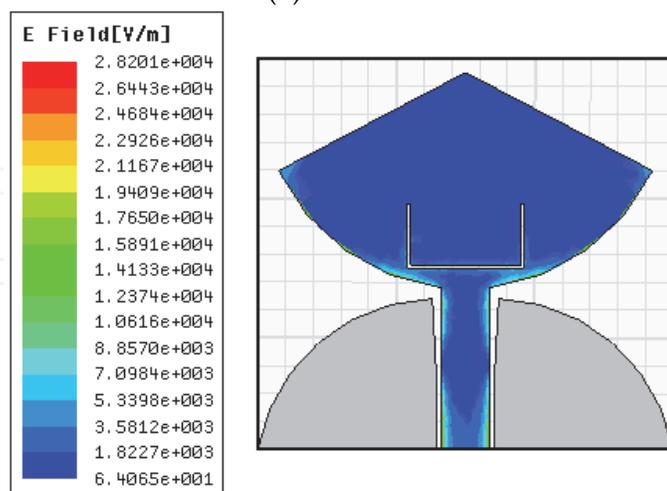
Fig. 5. Simulated VSWR of antenna B compared to antenna A



(a) 3.5 GHz



(b) 5.5 GHz



(c) 7.5 GHz

Fig. 6. Simulated current distribution of antenna B at specific frequencies

Fig. 6(b). It reveals that the currents mainly concentrate over the area of the slot in the radiation patch. The impedance nearby the feed-point changes acutely making large

reflection at the desired notched frequency. Fig. 7 also shows the surface current around the slot of antenna B at the notch frequency at 5.5 GHz. At 5.5 GHz, current is around the U-shaped slot. The impedance is nearly zero at the top of slot and the impedance is very high nearby the antenna feeding. In this case, the high impedance at the feeding point leads to the desired impedance mismatching near the notch frequency at 5.5 GHz [10].

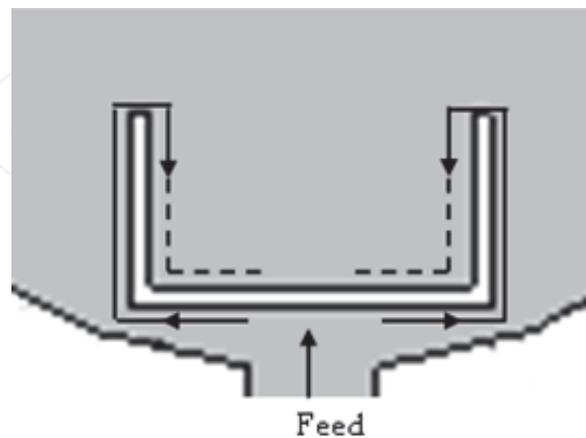


Fig. 7. Surface current around the slot of antenna B at the notch frequency at 5.5 GHz

By tuning various parameters, we can control the resonance frequency and quality factor to confirm the stop band. L_9 , L_{10} and w are key parameters to tune when the others are fixed. The effects of the lengths (L_9 , L_{10}) and width (w) of the U-shaped slot on band-notched performance of the antenna are analyzed below. Fig. 8 illustrates the VSWR for different values of L_9 . It is obvious that when L_9 becomes larger, the central frequency is reduced, and the edge of low frequency and the bandwidth are nearly unchanged. Fig. 9 shows the band-notch characteristics with different L_{10} , the behavior is similar to changing L_9 . When L_{10} is increasing from 4.1 mm to 5.1 mm, the edge of low frequency and the bandwidth is nearly unchanged. However, the central frequency of the notched band is decreased. In Fig. 10, the central frequency increases as w increases. The bandwidth is shortened when the width (w) of the slot decreases from 0.3 mm to 0.1 mm. The antenna gain of the antenna B is shown in Fig. 11. The figure indicates that, the proposed antenna has good gain flatness except for in the stop-band. The antenna gain variations are less than 4 dB throughout the desired UWB frequency band, and a sharp gain drop of about 7 dB occurs at 5.5 GHz.

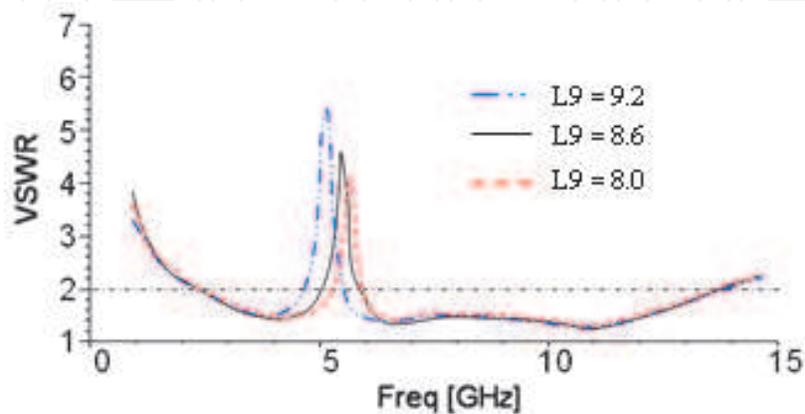


Fig. 8. Simulated VSWR for various L_9 when $L_{10} = 4.6$ mm and $w = 0.2$ mm

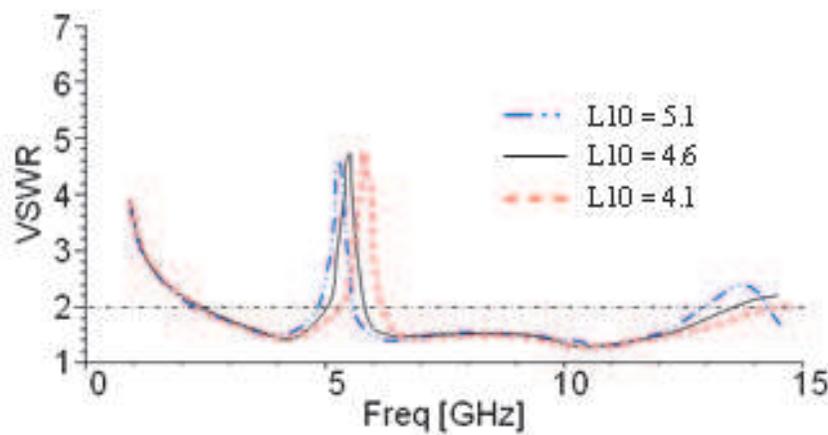


Fig. 9. Simulated VSWR for various L_{10} when $L_9 = 8.6$ mm and $w = 0.2$ mm

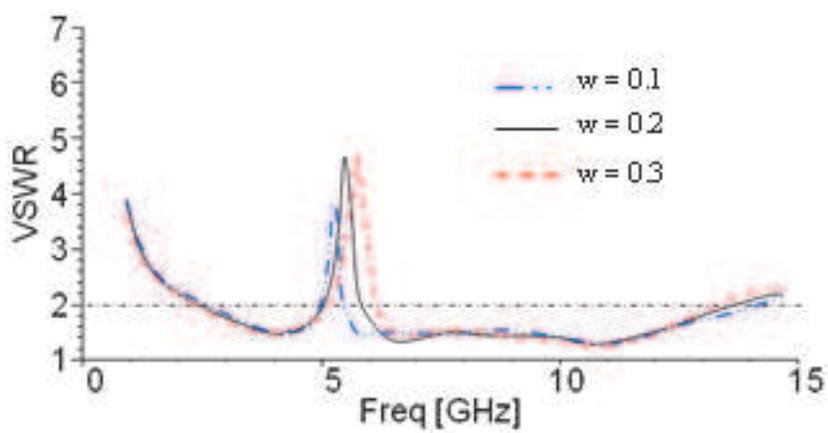


Fig. 10. Simulated VSWR for various w when $L_9 = 8.6$ mm and $L_{10} = 4.6$ mm

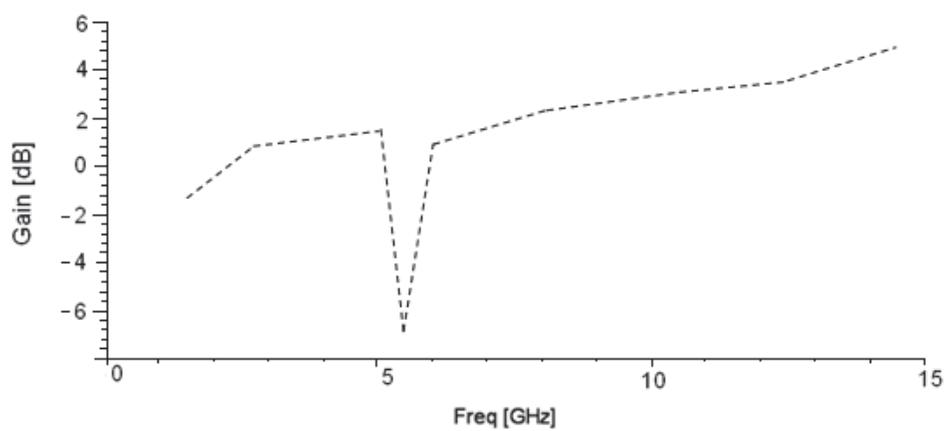


Fig. 11. Simulated gain of antenna B

To further explain the principle of the band-notched structures and how the center frequencies and bandwidths can be controlled an LC circuit model has been extracted for the proposed antenna A as shown in Fig. 12. Approximately, the radiating element of UWB antenna can be seen as several RLC parallel cells in series. The equivalent circuit input impedance can be expressed as

$$Z_R = \sum_{k=1}^n \frac{j\omega R_k L_k}{R_k (1 - \omega^2 C_k L_k) + j\omega L_k} \quad (2)$$

To simplify the calculation, only the real part is considered to determine the values of components with the formula

$$R_R = \sum_{k=1}^n \frac{R_k}{1 + R_k \left(\frac{1}{2\pi f L_k} - 2\pi f C_k \right)^2} \quad (3)$$

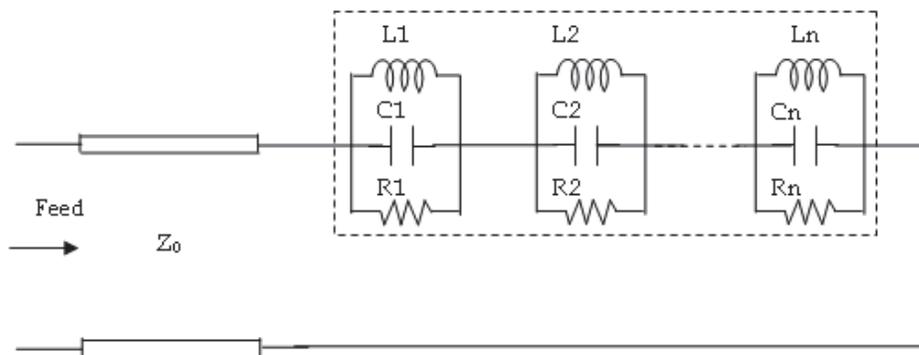


Fig. 12. Impedance model for radiating element of UWB antenna A

Fig. 13 shows the equivalent circuit model for radiating element of UWB antenna B. L_e and C_e indicate the inductor and capacitor values of the slot resonator. When the current propagates along the edge of the slot, an inductance should be introduced to the model. The narrow slot is equivalent to a capacitor. Increasing the length of the slot or decreasing the slot width is similar to increasing the capacitor value in the parallel LC circuit. On the other hand, increasing the length of slot will also lead to the increase of the inductor value [13]. Next we discuss bandwidth adjustment. For the parallel RLC resonator circuit as shown in Fig. 13, the input admittance is given by

$$Y_{in} = \frac{1}{R_R} + j\omega C_e + \frac{1}{j\omega L_e} \quad (4)$$

Where R_R represents the radiation resistance of the monopole element of antenna A. For a frequency near the resonant frequency [13]

$$\begin{aligned} \omega &= \omega_0 + \Delta\omega, \quad \omega_0 = \frac{1}{L_e C_e} \\ Y_{in} &= \frac{1}{R_R} + j\omega C_e + \frac{1}{j\omega L_e} \\ &= \frac{1}{R_R} + \frac{j}{\omega L_e} (\omega^2 L_e C_e - 1) \\ &= \frac{1}{R_R} + \frac{j}{\omega L_e} (2\omega_0 \Delta\omega + \Delta\omega^2) L_e C_e \\ &\approx \frac{1}{R_R} + j2C_e \Delta\omega \end{aligned} \quad (5)$$

In this case it is obvious that Y_{in} is similar to the input admittance of a parallel R and 2C circuit near 0 GHz. Then the -3dB bandwidth (BW) of the parallel RLC resonant circuit approximately equals twice the -3dB bandwidth of the parallel R and 2C circuit as shown in below [13]

$$BW = \frac{2}{R_R \times 2C_e} = \frac{1}{R_R C_e} \quad (6)$$

$$FBW = \frac{BW}{\omega_0} = \frac{1}{\omega_0 R_R C_e} \quad (7)$$

Where FBW represents the fractional bandwidth. Based on the above analysis we have a clear method for controlling the centre frequency and bandwidth of the notch. Increasing the length of the slots, which is similar to increasing the inductor value and the capacitor value, has the effect of decreasing the centre frequency and bandwidth [13]. Simulated results shown in Figs. 8 and 9 prove this conclusion. Fig. 10 shows the simulated VSWR for various width of the slot. It can be seen that, increasing the slot width is equivalent to decreasing the capacitor value, which ultimately leads to the rise of centre frequency and bandwidth of the notch band.

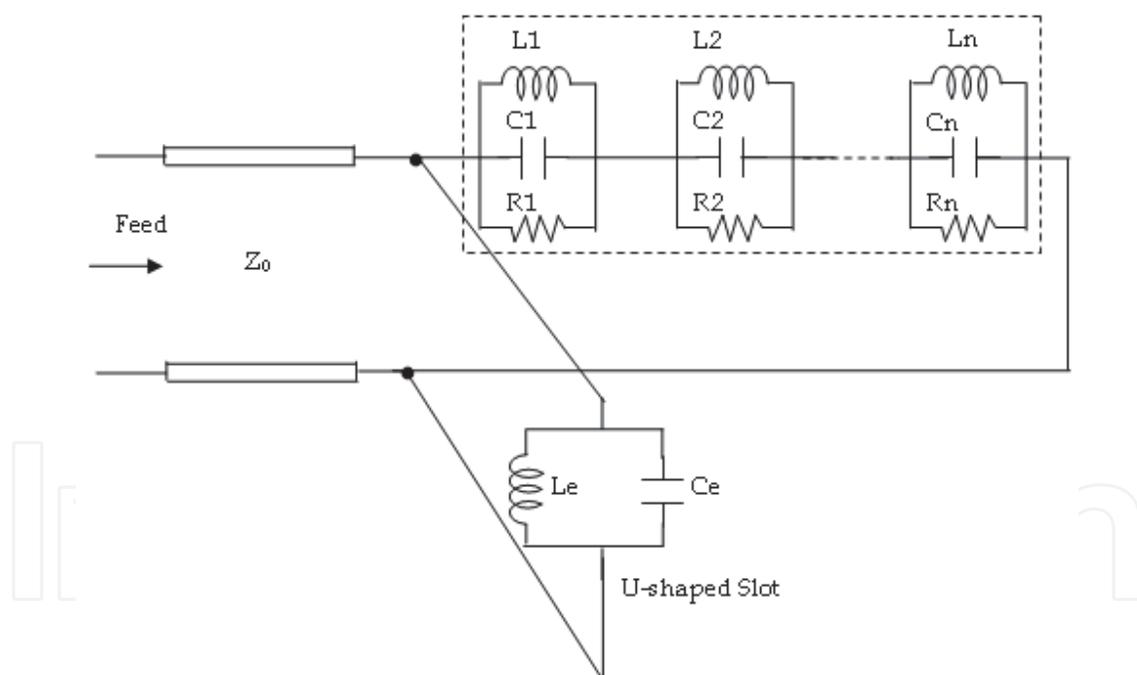


Fig. 13. Impedance model for radiating element of UWB antenna B

3.2 Dual band-notched UWB antenna design

Besides WLAN systems, IEEE 802.16 WiMAX from 3.3 to 3.6 GHz also operates in the UWB band. Dual notched bands are realized by using two nested U-shaped slots in the radiating patch (antenna A), which can yield band-notched characteristics centered at 3.4 GHz and 5.5 GHz. Fig. 14 shows the geometry and configuration of the UWB antenna (referred to as antenna C) with dual band-notched characteristics. It is note that, since the mutual coupling

exists between the exterior and interior U-shaped slots, the simulation values are not exactly equal to the prediction ones [10]. The optimized design parameters are $L11 = 5$ mm, $L12 = 11$ mm, $L13 = 5.1$ mm, $L14 = 10$ mm, $w1 = 0.3$ mm.

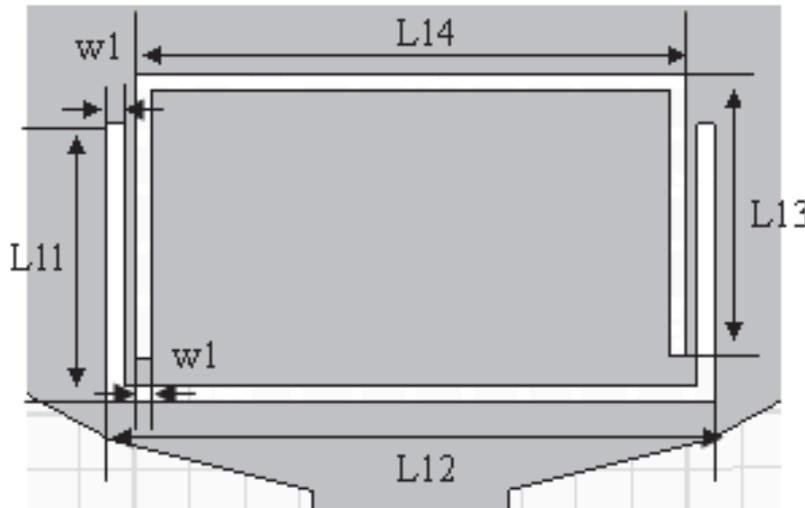


Fig. 14. Configuration of the proposed antenna C

Fig. 15 shows the simulated VSWR against frequency for the proposed antenna C. Results of the reference antennas without band-notched characteristics and with single band-notched characteristic are also shown for comparison. It is seen that the proposed antenna exhibits two notched bands of 3.3 to 3.5 and 5 to 6 GHz, while maintaining wideband performance from 1.8 to 15 GHz for $VSWR < 2$, covering the entire UWB frequency band. It is concluded that the notch bands for antenna C are indeed created by the two nested U-shaped slots. The simulated gain is shown in Fig. 16 and indicates a gain variation from 0.5 to 4.2 dB in the frequency range of 1.8 to 15 GHz. As can be expected, Sharp gain decreases occur both in 3.3 to 3.5 and 5 to 6 GHz bands. However, for other frequencies outside the rejected bands, the antenna gain is nearly constant in the entire UWB band. Fig. 17 shows the axial ratio against theta (spherical coordinate) for the proposed antenna C. It is observed that the whole axial ratio is greater than 3 dB, so the proposed antenna C is a linearly polarized antenna.

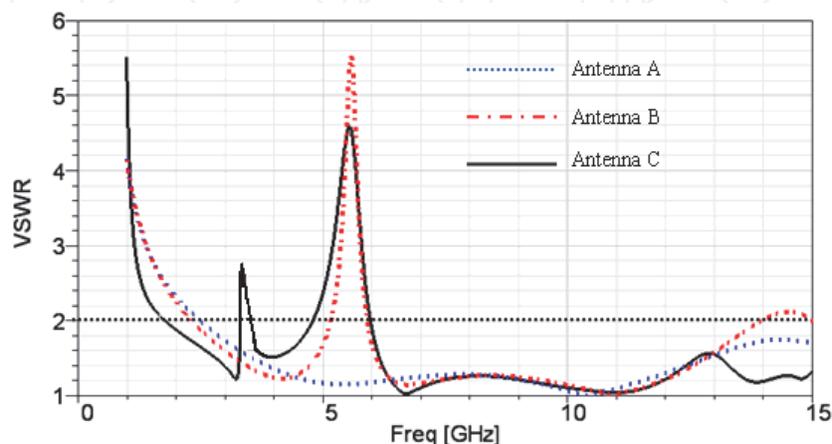


Fig. 15. Simulated VSWR of antenna C compared to antenna A and B

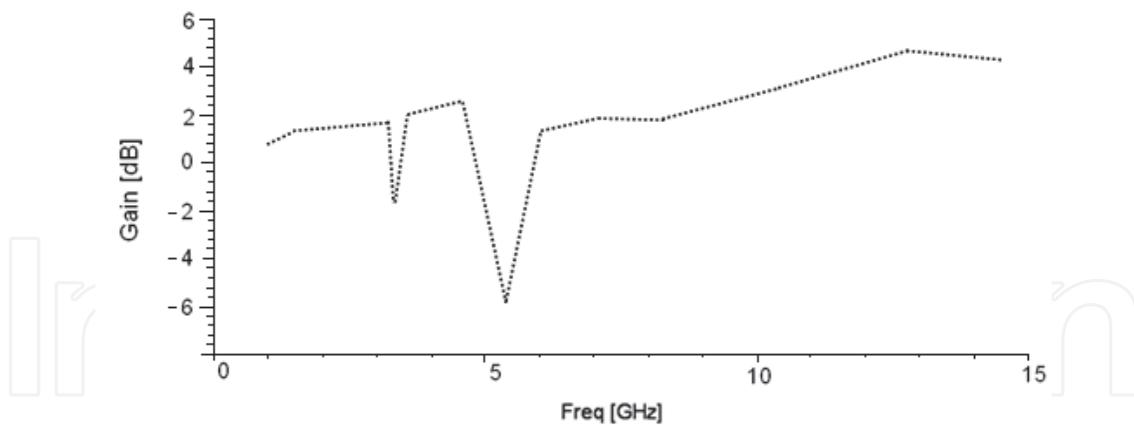


Fig. 16. Simulated gain of antenna C

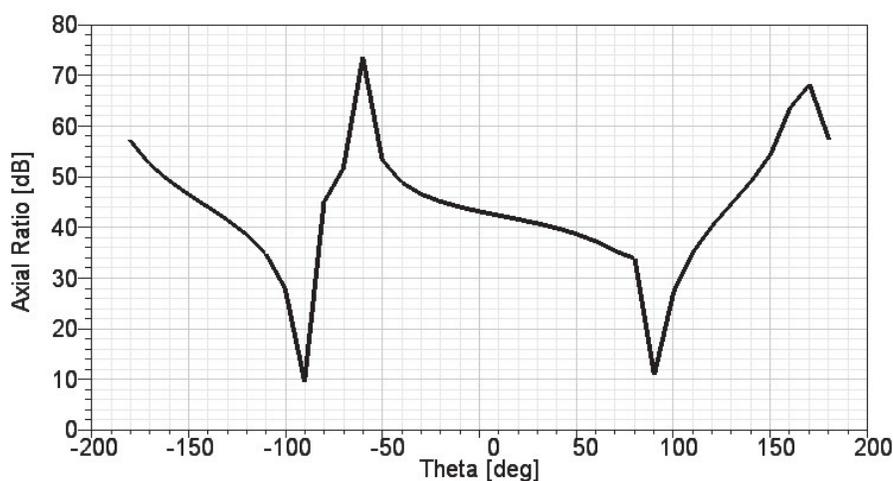


Fig. 17. Simulated axial ratio of antenna C

4. Radiation patterns and comparison

From the UWB applications point of view, the UWB antennas are usually required to have an omnidirectional radiation in the plane orthogonal to the radiating element. The radiation patterns at specific frequencies 3.2 GHz, 6 GHz, 9 GHz, 10.6 GHz and 13.5 GHz are simulated and illustrated in Fig. 18. The quasi-omnidirectional and symmetrical patterns in H plane in the whole band are obtained, which are necessary in a UWB communication system. The interference of high modes in high frequency is reduced. As a result, the proposed antenna can be used in several applications to compensate the drawback of the antennas at the whole frequency band from 3.1 to 10.6 GHz.

It is note that, the radiation patterns of antenna A and antenna B are not depicted. From the analysis by the Reference [10], the proposed band-notched structures including the single band-notched and dual band-notched ones have little influence on the radiation patterns of the UWB antenna. Tab. 1 summarizes the performances and compares this design to recently published UWB antennas with stop-band characterization. From Tab. 1, we can see that some of the antennas have only one notched band; others which have two notched bands, but the operation frequency band is not wide. When comparing the results to the

performance of some UWB antennas presented in Tab. 1, the following features of the implemented antenna can be highlighted: wide impedance bandwidth, good band-notch characteristic, compact in size and good gain flatness.

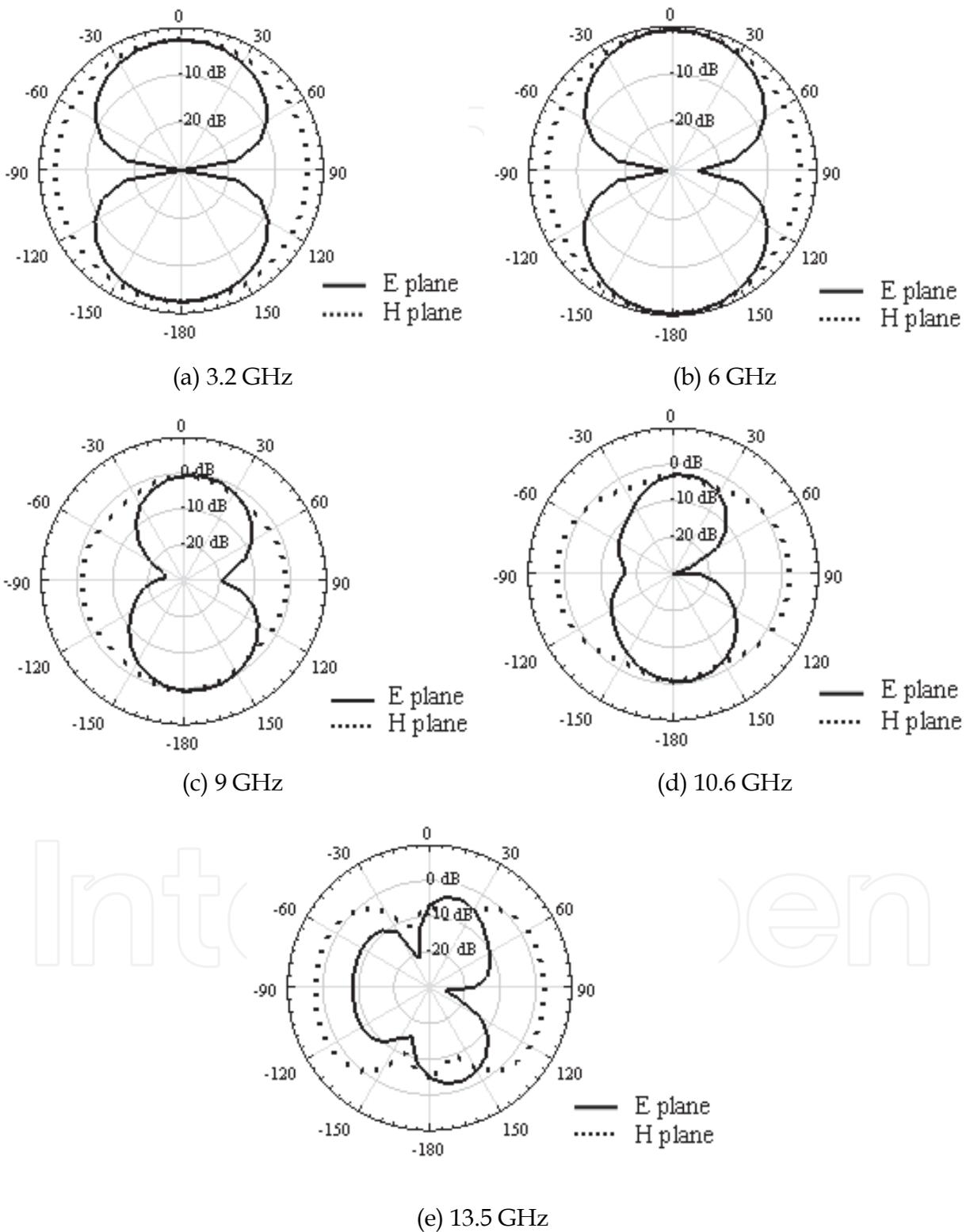


Fig. 18. Simulated radiation patterns at specific frequencies

Authors	Substrate material	Method of achieve stop-band	Operating bandwidth (GHz)	Relative bandwidth	Stop-band bandwidth (GHz)	Antenna size (mm ²)	Gain (dB)
Mehdipour, A. <i>et al</i>	Rogers RT Duroid 3003	embedding a ω -shaped slot	3.0 - 11	114 %	5.4 - 5.95	35 × 35	---
Nikolaou, S. <i>et al</i>	liquid crystal polymer	inserting a U-shaped slot	3.0 - 12	120 %	5.0 - 6.0	38.7 × 26.88	< 4.2
Yu, F. <i>et al</i>	FR4	embedding a C- shaped slot	3.0 - 23	153.8 %	5.0 - 6.0	28 × 30	0.2 - 3.9
Kim, Y. <i>et al</i>	FR4	inserting a V-shaped slot	2.8 - 10.6	116.4 %	$f_c = 5.25$	22 × 31	0.8 - 5.0
Chu, Q.-X. <i>et al</i>	FR4	embedding two nested C-shaped slots	3.1 - 10.6	> 91.3 %	$f_{c1} = 3.4$ $f_{c2} = 5.5$	26 × 30	2 - 5
Luo, J. <i>et al</i>	FR4	embedding an E-shaped slot in the patch and a U-shaped slot in the ground	2.87 - 10.91	116.6 %	3.49 - 4.12 5.66 - 6.43	35 × 14	----
This work	FR4	embedding two nested U-shaped slots	1.8 - 15	> 157.1 %	$f_{c1} = 3.4$ $f_{c2} = 5.5$	28 × 30	0.5 - 4.2

Table 1. Comparison between recently proposed antennas and this antenna

5. Conclusion

In this paper, a CPW-fed novel planar ultra-wideband antenna with dual band-notch characteristics was presented. One right-angle triangle was simulation removed from both two upper corners of the rectangular UWB antenna combined with an arc-shaped bottom and with a tapered arc-shaped ground plane. The simulation result of the VSWR demonstrates that the antenna has very broadband impedance which covers the frequency range of 1.8 to over 15 GHz. By embedding two nested U-shaped slot in the radiating patch, two frequency band notches between the bandwidth of 3.3 to 3.5 GHz and 5 to 6 GHz for WiMAX and WLAN have been obtained. Stable radiation patterns and constant gain in the UWB band are also obtained. Simulated and analyzed in detail in this paper, the proposed antenna could be a good candidate for UWB communication applications.

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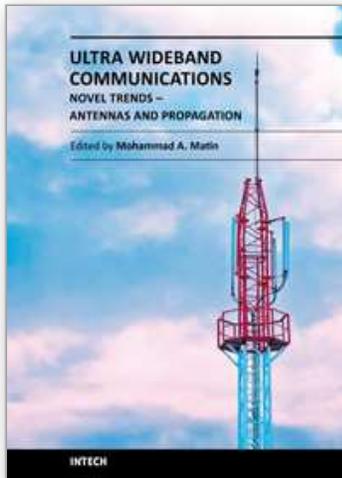
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This book explores both the state-of-the-art and the latest achievements in UWB antennas and propagation. It has taken a theoretical and experimental approach to some extent, which is more useful to the reader. The book highlights the unique design issues which put the reader in good pace to be able to understand more advanced research.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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