A Circular Slot UWB Antenna with Independently Tunable Quad-Band Filtering Characteristics

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Abstract ─ An effective design method is proposed to develop an excellent performed quad-band filtering UWB antenna. A spiral-shaped stub (SSS), two T-shaped stubs (TSSs) and an arc-shaped slot (ASS) are utilized to realize the proposed quad-band filtering characteristics. The independently tunable band-notched characteristics are carried out by adjusting the dimensions of SSS, TSS and ASS respectively. The proposed quad-band filtering UWB antenna is fabricated and measured for validation. The simulated and measured results show that this antenna can provide a wide bandwidth covering 3.1-10.6 GHz with four band notched characteristics and omnidirectional radiation patterns in its H-plane, which render it suitable for indoor UWB communication applications.

Index Terms ─ Notch band, quad-band notch characteristics, stub, UWB antenna.

I. INTRODUCTION

Since the Federal Communication Commission allocated the 3.1-10.6 GHz band for commercial ultra-wideband (UWB) communication systems, many research efforts have been put into UWB communication technology in both industry and academy [1]. As one of the key components of the UWB system, designing of UWB antennas has been widely studied to achieve wide impedance matching, stable radiation patterns and small size for various portable UWB systems [2-7]. However, some existing narrowband systems over the allocated UWB frequency band have been extensively studied and widely used, such as 3.3-3.7 GHz WiMAX band, 3.9-4.2 GHz C-band, 5.15-5.825 GHz WLAN band, the downlink of X-band satellite communication system operating at 7.25-7.75 GHz and ITU band operating at 8.025-8.4 GHz. As a result, these existing narrowband systems may give potential interferences to the UWB system. In order to eliminate or reduce the unwanted interferences from mentioned narrowband systems above, a great number of UWB antennas with single or dual band notched characteristics have been designed and their performances have been well investigated in the previously arts [8-15]. Most of these UWB antennas have only single or two notch bands, which limit their applications when more than two narrowband interferences happen simultaneously. Recently, several UWB antennas with triple or quadruple band notched have been designed and their performance has been experimentally verified [16-21]. However, most of these band notches are realized by etching various slots on the radiating patch or ground plane, which may leak extra electromagnetic waves. In addition, parasitic strips, open circuit stubs and stepped impedance resonator [22-29] are also employed to develop multiple notch band UWB antennas. Although several band-notched UWB antennas have been designed with triple or four notch bands, they have complex structures which include holes and multilayered substrates. Additionally, some of these four band-notched UWB antennas are large in size, which limit their utilization. Owing to the limits of the space in the modern portable terminals, it is a real challenge to design a compact UWB antenna with multiple band-notched characteristics.

For these reasons, an effective design method is proposed to develop an excellent quad-band filtering UWB antenna. The proposed antenna is designed on the basis of a wide slot UWB antenna with a ring shaped radiating patch. A spiral-shaped stub (SSS), two T-shaped stubs (TSSs) and an arc-shaped slot (ASS) are employed to develop quad-band filtering bands operating at 3.5 GHz,

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4.1 GHz, 5.5 GHz and 7.8 GHz to filter out the potential narrowband interferences from WiMAX, C-band, WLAN and X-band. To utilize the limited space, the T-shaped stubs are inserted into the ring shaped radiating patch with an isolation element. By optimizing the dimensions and position of the SSS, TSSs and ASS, four designated band notches are achieved to prevent the interferences from the aforementioned narrowband systems. The proposed antenna is fabricated and measured to verify the design effectiveness with respect to its frequency characteristics, including impedance bandwidth, tunable notch band, radiation patterns and gain.

II. ANTENNA DESIGN

The configuration of the proposed quad-band filtering UWB antenna is demonstrated in Fig. 1. The proposed antenna is printed on a substrate whose relative permittivity, loss tangent and thickness are 2.65, 0.002, and 1.6 mm, respectively. For this antenna, it consists of a wide slot with circular shaped that is etched on the CPW ground plane, a circular ring-shaped radiating patch, an SSS, two TSSs, an ASS, an isolation element between the upper TSS and the lower TSS, and a CPW ground plane together with a 50-Ohm CPW feed structure. The 50-Ohm CPW feed structure is comprised of a CPW-fed transmission line whose width is W1=3.6 mm, and a gap g with a width of 0.2 mm. In this design, the upper TSS is used to generate the lowest notch band operating at 3.5 GHz band, while the 3.9-4.2 GHz C-band is given by the lower TSS. The SSS is employed to provide a notch operating at 5.5 GHz WLAN band and the ASS is designed to prevent the potential interferences from the ITU band or X-band around 8 GHz. The proposed antenna has been investigated and optimized by the HFSS. The center frequencies of these notch bands can be tuned by adjusting the dimensions of the SSS, TSSs and ASS to render the proposed notches suitable to filter out the aforementioned narrowband interferences. The antenna is well optimized and the optimal structure parameters are listed as follows: L=32 mm, W=24 mm, L1=5.9 mm, L2=7 mm, L3=3.7 mm, L4=4.6 mm, L5=1.9 mm, L6=2.3 mm, L7=2.8 mm, L8=4.2 mm, L9=1.1 mm, W1=3.6 mm, R=11.8 mm, r1=6.7 mm, r2=5 mm, r3=12.5 mm, r4=12.3 mm, g=0.2 mm, g1=0.5 mm, g2=0.3 mm, g3=0.2 mm, d1=0.8 mm, d2=0.8 mm, d3=0.6 mm, d4=0.4 mm, d5=2.1 mm, d6=0.4 mm, s=0.2 mm, and Theta=29°.

The design procedure of the proposed quad-band filtering UWB antenna is summarized as follows. Firstly, a circular wide slot UWB antenna is designed to cover a wide UWB band ranging from 3.1 GHz to 10.6 GHz. Next, the SSS, ASS and TSSs are integrated into the circular wide slot UWB antenna step by step to reject the designated four narrowband bands. Each band-notch structure will be integrated into the UWB antenna to fine-tune the dimensions. Finally, all four band-notched elements and the UWB antenna are put together and optimized for desired performance. In this design, each band-notch structure, namely ASS, SSS, upper TSS and lower TSS, is responsible for creating four frequency filtering bands. Here, total resonance length of each notch band is mainly determined by the lengths of the band-notch structures. The center frequency of each band-notch is approximately given by using the following formulas:

$$f_{notch} = \frac{c}{2L_{ASS(or\ TSSs\ or\ SSS)}\sqrt{\varepsilon_{eff}}}, \tag{1}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2}, \tag{2}$$

where $L_{ASS(or\ TSSs\ or\ SSS)}$ is the total resonance length of each band-notch structure, ε_r is the relative permittivity, ε_{eff} is the effective dielectric constant and c is the speed of light. At the beginning, the initial lengths of the ASS, SSS and TSSs are theoretically calculated based on the above formulas and then a simulation solver HFSS is utilized to get the optimal dimensions to tune the desired center frequencies of the notches.

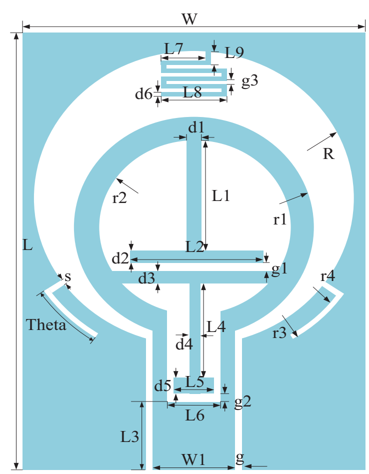


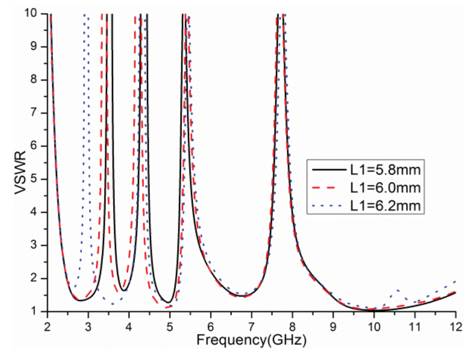
Fig. 1. Geometry of the proposed antenna.

III. PERFORMANCE OF THE PROPOSED ANTENNA

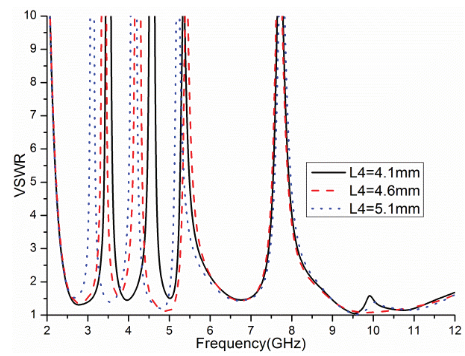
In this section, parameters L1, L4, L8 and Theta are selected to investigate the independently tunable band-notched characteristics. Figure 2 (a) shows the effects of L1 on the impedance matching of the proposed quad-band filtering UWB antenna. It can be seen that the center frequency of the lowest notch band moves to the low frequency with an increase of L1. When L1 increases from 5.8 mm to 6.2 mm, the center frequencies of the lowest notch band move from 3.6 GHz to 3.0 GHz. This is attributed to the prolonged resonance length of upper TSS and the coupling between the upper TSS and the isolation element.

Figure 2 (b) depicts effects of L4 on the band-notched function. It is found that the center frequency of the 4.2 GHz notch band shifts toward low frequency when L4 increase from 4.1 mm to 5.1 mm, which is caused by the increased resonance length of lower TSS. Additionally, the upper and lower TSS can affect both the lowest notch band and 4.2 GHz notch band because they interact with each other through the isolation element. Figure 2 (c) gives the effects of the parameter L8 on the notch band characteristics. It is observed that the center frequency of 5.5 GHz notch band shifts from 5.7 GHz to 5.2 GHz as L8 increasing from 3.9 mm to 4.5 mm. Additionally, the center frequencies of the other notch bands remain constant. The expended L8 not only increases the resonance of the SSS but also enhances the coupling between the SSS and the circular slot. Thus, the notch moves from high frequency to low frequency with a reducing notch bandwidth. Figure 2 (d) demonstrates the effects of Theta on the tunable notch band characteristics. We note that the center frequency of the highest notch band shifts toward lower frequency with an increment of Theta. With an increase of Theta ranging from 27° to 30°, the resonance length of the ASS is prolonged, and hence, the center frequency of the highest notch band corresponding to the quarter wavelength resonance moves to low frequency. From the discussions above, we can conclude that the center frequencies of these proposed notch bands are tunable by adjusting the dimensions of the ASS, TSSs and SSS. The lowest band-notch is generated by the upper TSS, while the 4.2 GHz band-notch is produced by the lower TSS. The 5.5 GHz WLAN band-notch is realized by using an SSS inserted inside of the circular wide slot and the highest band-notch is implemented by the ASS that is embedded in the CPW ground plane.

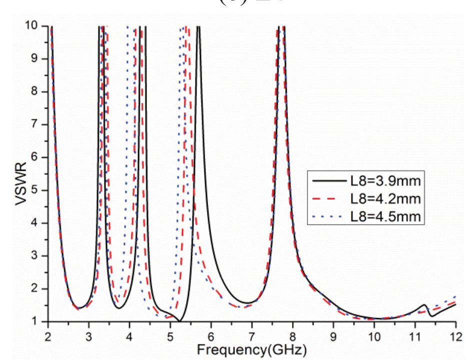
In order to further understand the principle of the proposed antenna, the surface current distributions are investigated by the HFSS and the simulated results are shown in Fig. 3. Figure 3 (a) shows the surface current distribution at 3.5 GHz notch band. It is found that the current distribution mainly flows along the upper T-shaped stub. However, the upper T-shaped stub has some effects on the lower T-shaped stub via the isolation element inserted in the circular ring radiating patch. As for the 4.2 GHz band-notch, the surface current mainly focuses on the lower T-shaped stub, which can determine its center frequency, and the result is shown in Fig. 3 (b). When the band-notch appears at 5.5 GHz, the surface current concentrates on the spiral shaped stub and its effect is shown in Fig. 3 (c). In this case, the current on the CPW ground plane, T-shaped stubs and the arc-shaped slot are small. Thus, the spiral shaped stubs mainly affect the band-notch characteristics of the 5.5 GHz WLAN band. As for the 7.8 GHz notch band, it can be observed that the strong current distribution flows along the arc-shaped slot.



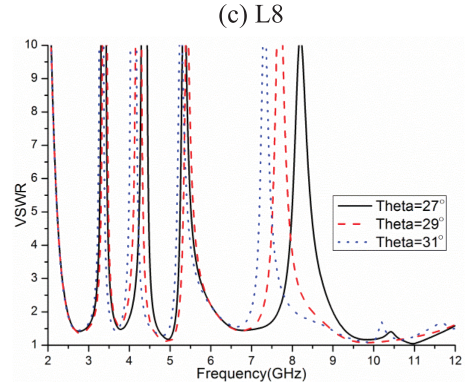
(a) L1



(b) L4

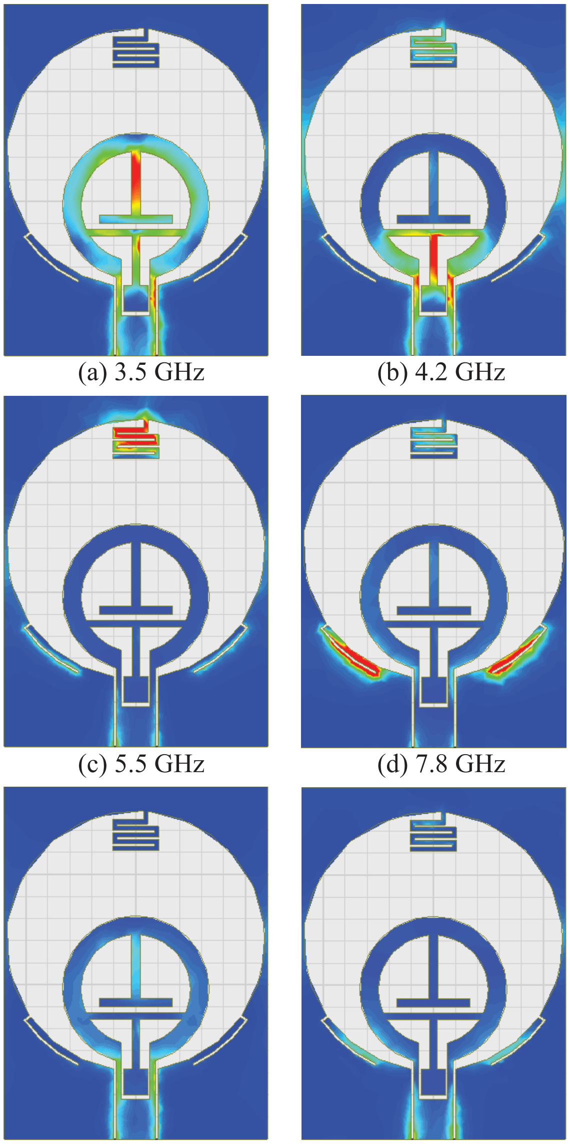


(c) L8



(d) Theta

Fig. 2. Parameter effects on the band-notched characteristics of the proposed antenna.



(a) 3.5 GHz (b) 4.2 GHz

(c) 5.5 GHz (d) 7.8 GHz

(e) 3.1 GHz (f) 10 GHz

Fig. 3. Current distribution of the proposed antenna.

From the current distributions, we can see that the current distributions mainly concentrate on the corresponding band-notch structures, and hence, affect the band-notch characteristics that have been verified in Fig. 2. Thus, we can say that the energy cannot effectively radiate at the above designated notch bands, and hence, four notch bands are formed to prevent the potential narrowband interferences from the mentioned narrowband systems. At the operating bands such as 3.1 GHz and 10 GHz, the surface currents distribute on the CPW-fed structures and the circular wide-slot, while the current on the arc-shaped slot, T-shaped stubs and spiral shaped stub are weak; which indicates that the existence of band-notch structures has little effects on the UWB antenna at pass-band frequencies.

IV. RESULTS AND DISCUSSIONS

In order to verify the performance of the quad-band filtering UWB antenna, the proposed antenna has been optimized, fabricated and measured in an anechoic chamber. The prototype of the fabricated antenna is shown in Fig. 4. The measured impedance characteristics of the fabricated antenna in comparison with the optimized curve are shown in Fig. 5, which is obtained by using Agilent N5224A vector network analyzer. It can be seen that the proposed antenna covers the entire UWB bandwidth except for the designated four notch bands, which aim to suppress the potential interferences from 3.5 GHz WiMAX band, 4.2 GHz C-band, 5.5 GHz WLAN band and 8 GHz X-band. Also, the measured VSWR agrees well with the simulated one, which helps validate the results from the HFSS. The arc-shaped slot, T-shaped stubs and spiral shaped stub function as filters, which produce non-resonance characteristics in the corresponding notch bands. The deficiencies between the measured and simulated VSWRs are attributed to the fabrication tolerance and manual welding inaccuracies.

Fig. 4. Fabricated antenna.

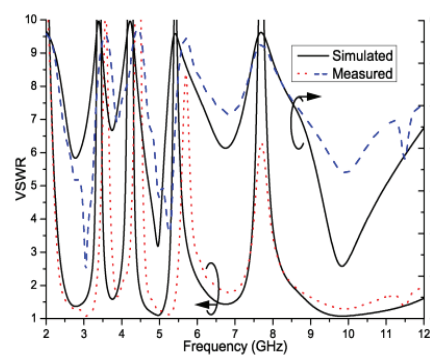
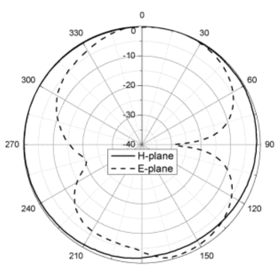
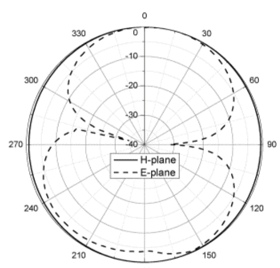


Fig. 5. Measured VWSR and S_{11} of the antenna.

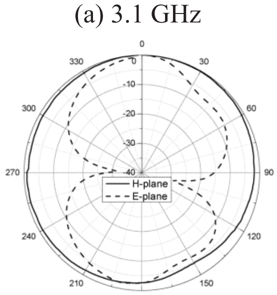
The radiation patterns of the proposed quad-band-notched UWB antenna are measured at 3.1 GHz, 3.9 GHz, 5.0 GHz, 6.5 GHz and 9.0 GHz, which are shown in Fig. 6. It is found that nearly omnidirectional radiation patterns are obtained in the H-plane, while a figure of 8-like radiation patterns is achieved. Though the fabricated antenna can provide omnidirectional radiation patterns that are suitable for UWB applications, the radiation patterns are distorted in the E-plane at high frequencies, which is caused by the leaky electromagnetic waves given by the designed band-notch structures. The measured gains versus the frequency are obtained by comparing the proposed quad-band-notched UWB antenna to that of a standard horn antenna in an anechoic chamber and the measured results are shown in Fig. 7. It is clearly shown that there is a significant gain reduction at the notch bands, which drop quickly to -5.2 dBi at WiMAX band, -3.8 dBi at 4.2 GHz C-band, -2.9 dBi at WLAN band and -2.2 dBi at X-band. Additionally, the proposed antenna has a stable gain in the entire UWB operating band out of the designed four notch bands. From the discussions above, we can see that the proposed UWB antenna can provide good quadruple frequency rejection characteristic and nearly omnidirectional radiation patterns. The radiation efficiencies of the proposed antenna at the entire UWB operation band are above 84%, while the radiation efficiencies are 25%, 29%, 40% and 48% at the notches for WiMAX band, C-band, WLAN band and X-band, respectively.



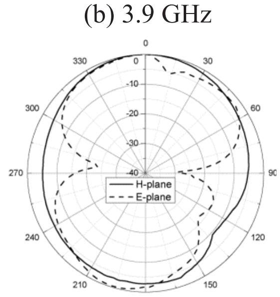
(a) 3.1 GHz



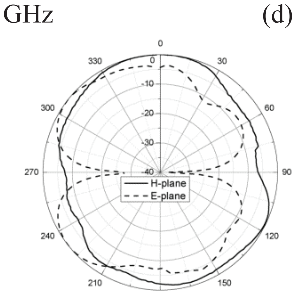
(b) 3.9 GHz



(c) 5.0 GHz



(d) 6.5 GHz



(f) 9.0 GHz

Fig. 6. Radiation patterns of the proposed antenna.

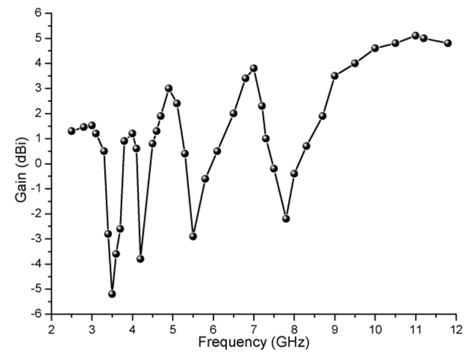


Fig. 7. Gains of the proposed antenna.

V. CONCLUSION

A CPW-fed quad-band-notched UWB antenna with independently tunable band-notch characteristics has been proposed to solve the interference problem and its performance has been verified both numerically and experimentally. The quad-band-notched characteristics are realized by using slot and stub technologies, namely, an arc-shaped slot, a spiral shaped stub and two T-shaped stubs. The independent tunable band-notch characteristics, current distribution, radiation patterns and gains have been studied and discussed in detail. The numerical and experimental results demonstrated that the proposed antenna had a wide bandwidth, quad-band-notch characteristics, stable omnidirectional radiation patterns and appropriate gains, indicating that the antenna is a good candidate for band-notch UWB communication applications.

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