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Quadruple Band-Notched Trapezoid UWB Antenna with Reduced Gains in Notch Bands

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Abstract

A compact ultra-wide band antenna with a quadruple band-notched characteristic is proposed. The proposed antenna consists of a slotted trapezoid patch radiator, an inverted U-shaped band stop filter, a pair of C-shaped band stop filters, and a rectangular ground plane. To realize the quadruple notch-band characteristic, a U-shaped slot, a complementary split ring resonator, an inverted U-shaped band stop filter, and two C-shaped band stop filters are utilized in this antenna. The antenna satisfies the −10 dB reflection coefficient bandwidth requirement in the frequency band of 2.88–12.67 GHz, with a band-rejection characteristic in the WiMAX (3.43–3.85 GHz), WLAN (5.26–6.01 GHz), X-band satellite communication (7.05–7.68 GHz), and ITU 8 GHz (8.08–8.87 GHz) signal bands. In addition, the proposed antenna has a compact volume of 30 mm× 33.5 mm× 0.8 mm while maintaining omnidirectional patterns in the H-plane. The experimental and simulated results of the proposed antenna are shown to be in good agreement.

Key Words: Band-Stop Element, Four Notches, Radiation Pattern, Reduced Gain, Ultra-Wide Band.

I. INTRODUCTION

Since the US Federal Communications Commission allocated the frequency band from 3.1 GHz to 10.6 GHz for ultra-wide band (UWB) systems, UWB technology has attracted a great deal of interest due to its low cost, low complexity, and extremely high data rate transmission capabilities for short range communication. In addition, UWB systems are resistant to severe multipath and jamming environments [1]. However, UWB systems potentially cause interference with coexisting wireless communication systems, such as the WiMAX (3.3–3.6 GHz), WLAN (5.15–5.82 GHz), and X-band (7.9–8.7 GHz) signal bands. Therefore, UWB antennas should ideally have band notch functions.

To avoid potential interference, UWB antennas with single [2–6], dual [7–11], or triple [12–15] band rejection functions have been presented. Recently, UWB antennas with quadruple notch bands [16, 17] have also been reported. However, these antennas do not have good rejection levels of peak gains in all desired notch bands. Selectively creating a narrow stop band and a wide stop band for different notch bands is challenging. For example, the WiMAX band has a relatively narrow band (300 MHz), whereas the WLAN (675 MHz), X-band (500 MHz), and ITU 8 GHz (800 MHz) bands have relatively wider bands. Therefore, establishing different ways of achieving the band rejection characteristic for each notch band is preferable.

To resolve the task of selectively obtaining the different notch band bandwidths, a trapezoidal UWB antenna with quadruple notch slots, filters, and a complementary split ring resonator (CSRR) to design the proposed band-notched characteristic considering the space limitation imposed on the

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antenna and band rejection elements. The proposed antenna structure is simulated using the ANSYS High-frequency Structure Simulator (HFSS), which is a commercial 3-D full-wave electromagnetic simulation program. The simulation and measurements both indicate quadruple band rejection with central frequencies of 3.5 GHz (WiMAX), 5.5 GHz (WLAN), 7.4 GHz (X-band), and 8.4 GHz (ITU 8 GHz band) with excellent quadruple band-notched characteristics.

II. Antenna Configuration

Fig. 1(a) depicts the geometry of the proposed trapezoid UWB antenna. The dimensions of the optimized antenna

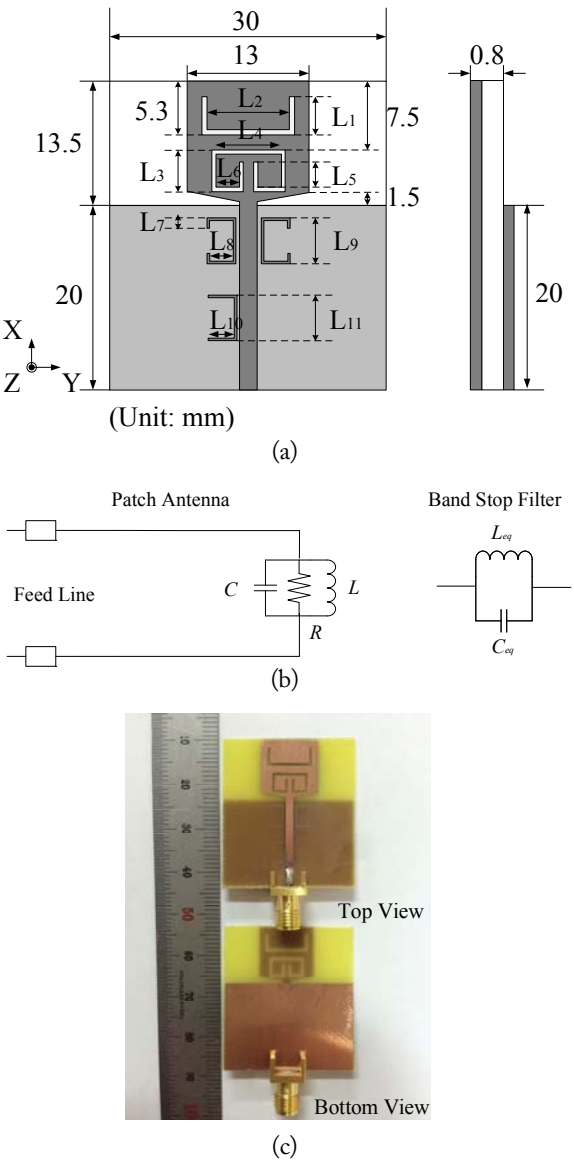


Fig. 1. Antenna configuration: (a) geometry of the proposed antenna, (b) equivalent circuit of the model of the patch antenna and the band-stop element, and (c) fabricated antenna.

Table 1. Optimized antenna parameters

Parameter	L_1	L_2	L_3	L_4	L_5	L_6	L_7
mm	4.2	10	4.5	8	3.2	3.5	1.2
Parameter	L_8	L_9	L_{10}	L_{11}	G_1	G_2	
mm	2.7	5	3.1	5	0.5	0.2	

are shown in Table 1. The antenna is designed on an FR-4 substrate with a thickness of 0.8 mm, relative permittivity of 4.4, and a loss tangent of 0.02. The proposed antenna is fed by a 50-Ω microstrip line. The equivalent circuit of the patch antenna and the band-stop element is shown in Fig. 1(b). The proposed design is optimized by considering several aspects, such as the size of the band-stop elements, bandwidth of the antenna, bandwidth of the notch bands, level of band rejection, and radiation patterns. Considering the relatively sharp and narrow bandwidth of the notched WiMAX band, a CSRR structure is used as a band rejection element in the proposed antenna because CSRRs are electrically small RLC resonant elements with a high quality factor at microwave frequency. The length of the CSRR is $L_a = L_4 + 2(L_3 + L_5 + L_6) = 30.4$ mm. To generate a relatively wide notch band for X-band satellite communication, a pair of C-shaped band stop filters is placed on both sides of the transmission line. The length of the single C-shaped band stop filter is $L_b = L_9 + 2(L_7 + L_8) = 12.8$ mm. To obtain relatively wide-notched WLAN and ITU 8 GHz signal bands, a U-shaped slot and a U-shaped band stop filter are utilized in the proposed antenna. The length of the slot is $L_c = 2L_1 + L_2 = 18.4$ mm, and the length of the filter is $L_d = 2L_{10} + L_{11} = 11.2$ mm. In designing the antenna, the total length of the proposed band-stop elements can be empirically approximated by

$$L_{total} \approx \frac{\lambda_g}{2} = \frac{\lambda_0}{2\sqrt{\varepsilon_{eff}}} = \frac{c}{2 f_{notch}\sqrt{\varepsilon_{eff}}} \tag{1}$$

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

where λ_0 is the free space wavelength, f_{notch} is the center frequency of the notch band, and c and ε_{eff} are the speed of light and the approximated effective dielectric constant, respectively. The length of the proposed band-stop elements approaches half of the guided wavelength ($\lambda_g/2$). The notch band frequency and fractional bandwidth of the band-stop elements, respectively, are

$$f_{notch} = \frac{1}{2\pi\sqrt{L_{eq}C_{eq}}} \tag{3}$$

$$FBW = \frac{f_2 - f_1}{f_{notch}} = \frac{1}{Q} \tag{4}$$

$$L_{eq} = \frac{R_{eq}}{2\pi f_{notch} Q} \tag{5}$$

$$C_{eq} = \frac{1}{4\pi^2 f_{notch}^2 L_{eq}} \tag{6}$$

where L_{eq} and C_{eq} are the equivalent inductance and capacitance, respectively, of the proposed equivalent circuit of the band-stop elements, FBW is the fractional bandwidth with the magnitude of the input impedance dropping to 0.707 of its peak value, Q is the quality factor, and R_{eq} corresponds to the real part of the input impedance at the notch band center frequency. The width of the CSRR and U-shaped slot is 5 mm, and the width of the C-shaped and U-shaped band stop filters is 0.2 mm. The gap between the C-shaped band stop filter and the transmission line is $G_1 = 0.5$ mm, and the gap between the U-shaped band stop filter and the transmission line is $G_2 = 0.2$ mm. To obtain an omnidirectional radiation pattern in the H-plane, a monopole type of the trapezoidal UWB antenna is used.

III. Analysis and Results

Fig. 1(c) shows a photograph of the fabricated antenna, and Fig. 2 depicts the measured and simulated S_{11} characteristics of the antenna. The designed antenna exhibits a wide bandwidth of 2.88–12.67 GHz, completely covering the WiMAX, WLAN, X-band downlink, and ITU 8 GHz signal bands with quadruple notch bands of 3.44–3.85 GHz, 5.26–6.01 GHz, 7.05–7.68 GHz, and 8.08–8.87 GHz, respectively.

Single Notch Band for WiMAX

To avoid interference with the WiMAX band, a single band-notched design with a CSRR structure is presented and analyzed in this section. The band-notched characteristic at the desired frequency can be obtained by adjusting the length of the CSRR to approximately half of a wavelength. The effects of four different lengths of the CSRR L_a on the reflection coefficient bandwidth are shown in Fig. 3(a). A sharp and narrow notch band is obtained when L_a is changed from 29.6 mm to 30.8 mm. With consideration of the required notch band and the limited space for inserting the band-stop elements, 30.4 mm is chosen for L_a in the design.

Fig. 3(b) illustrates the input impedance of the desired single band-notched structure for the WiMAX band. At a central frequency of 3.5 GHz, the imaginary component curve exhibits a parallel resonance characteristic, and the real part has a peak of around 400 Ω. The parallel resonant phenomenon opens the input terminal, so that the antenna cannot radiate efficiently at this frequency.

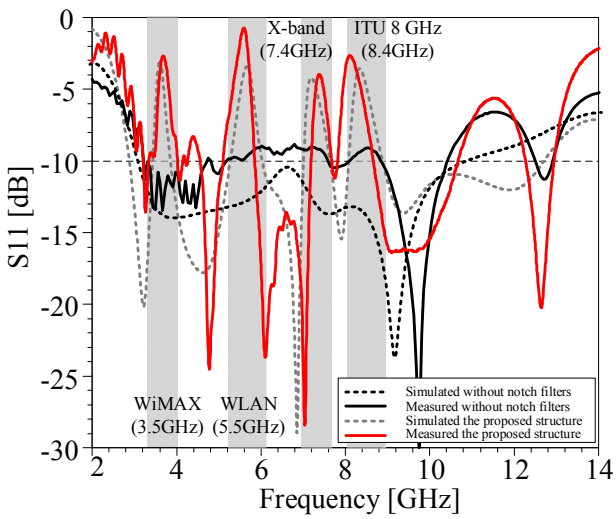
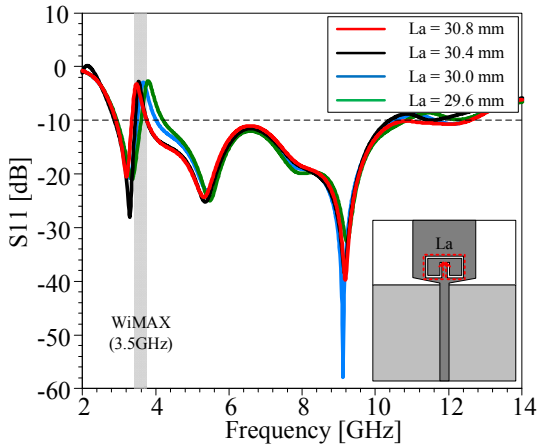
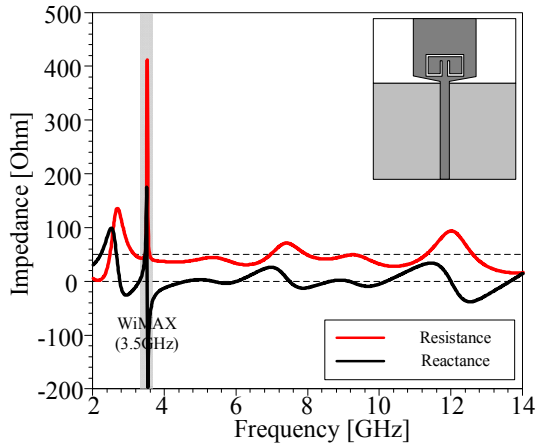


Fig. 2. Measured and simulated S_{11} characteristics of the proposed antenna.



(a)



(b)

Fig. 3. Antenna configuration: (a) S_{11} characteristics of the single notch band (WiMAX) for various L_a and (b) input impedance of the proposed single notch band for WiMAX.

Single Notch Band for WLAN

To suppress the unwanted WLAN band, a single band-notched structure with a U-shaped slot is presented and analyzed in this section. The band-notched characteristics at the desired frequency can be obtained by adjusting the length of the U-shaped slot to be approximately half of a wavelength. The effects of the key parameter corresponding to the four different lengths of the U-shaped slot L_c on the reflection coefficient bandwidth of the presented design are shown in Fig. 4(a). Wide notch bands are obtained when L_c is changed from 17.6 mm to 18.8 mm. With consideration of the required notch band and the space limitation for using a slot on the radiator, L_c is selected to be 18.4 mm.

Fig. 4(b) shows the input impedance of the required single band-notched design for the WLAN band. When the frequency is 5.3 GHz, the imaginary component approaches 10 Ω. When the frequency is 5.8 GHz, the imaginary part exhibits a parallel resonance, but the real part peaks at around 120 Ω. The series and parallel resonances at 5.3 and 5.8 GHz have minor effects on the impedance matching performance. Thus, radiation performance suffers in the WLAN band because of impedance mismatching.

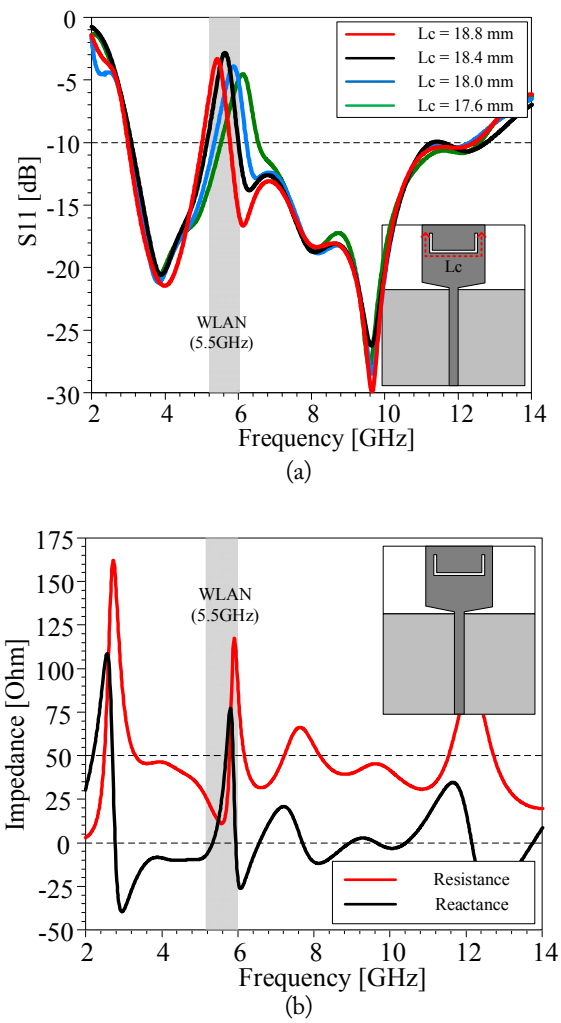


Fig. 4. Antenna configuration: (a) S_{11} characteristics of the single notch band (WLAN) for various L_c and (b) input impedance of the single notch band for WLAN.

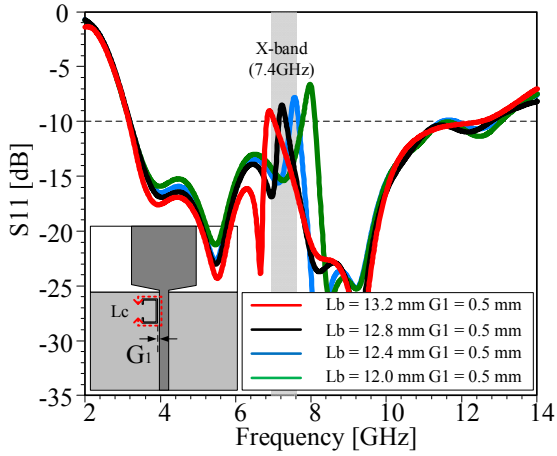


Fig. 5. S_{11} characteristics of the single notch band (X-band) for various L_a (G_1 = 0.5 mm).

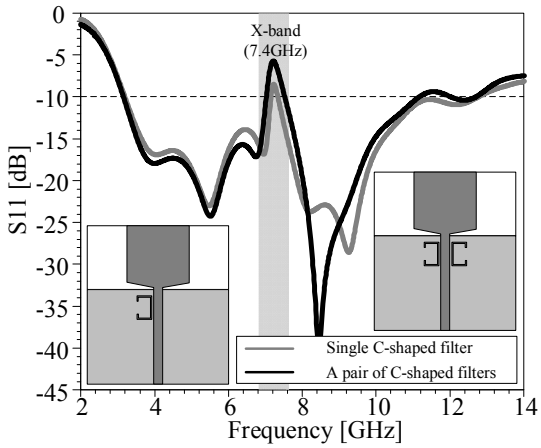


Fig. 6. S_{11} characteristics of the single notch band with a C-shaped filter and with a pair of C-shaped filters for the X-band.

Single Notch Band for X-band Satellite Communication

To minimize the potential interference with X-band satellite communication, a single band-notched design with a single C-shaped filter and a pair of C-shaped filters is presented and analyzed in this section. The band-notched characteristic at the desired frequency can be obtained by adjusting the length of the filter L_c to be approximately a half wavelength and by adjusting the gap G_1 between the constant gap G_1 = 0.5 mm on the reflection coefficient bandwidth. In Fig. 5, a relatively wide notch band is obtained when L_b is changed from 12.0 mm to 13.2 mm. The reflection coefficient bandwidth near 11 GHz decreases when L_b is smaller than 12.8 mm. Moreover, the performance of the band rejection level deteriorates when L_b is larger than 12.8 mm.

Thus, with consideration of the desired notch band, the S_{11} characteristics at high frequency, and the band rejection level, L_b is selected to be 12.8 mm. Although it covers the required notch band for the X-band, the total level of band rejection is still at a low level. Therefore, a pair of C-shaped filters is located on both sides of the transmission line. Fig. 6 shows the difference in the S_{11} characteristics of the single notch band with a single C-shaped filter and with a pair of C-shaped filters for the X-band. The band rejection level is better when locating a pair of C-shaped filters than a single filter. However, with a pair of C-shaped filters located on both sides of the transmission line, the reflection coefficient near 11 GHz deteriorates. To attain impedance matching near 11 GHz without destroying the band rejection level, the effect of the gap G_1 on the rejection level is analyzed in Fig. 7(a). The rejection coefficient near 10 GHz deteriorates when G_1 is smaller than 0.5 mm. Moreover, the band rejection level decreases when G_1 is larger than 0.5 mm. Consequently, G_1 is selected to be 0.5 mm.

The input impedance of the antenna with a single notch band for the X-band downlink is shown in Fig. 7(b). At 7.2 GHz, the imaginary component curve exhibits a series resonance characteristic, and the real part is close to 10 Ω. Therefore, the radiation performance deteriorates at this frequency because of impedance matching.

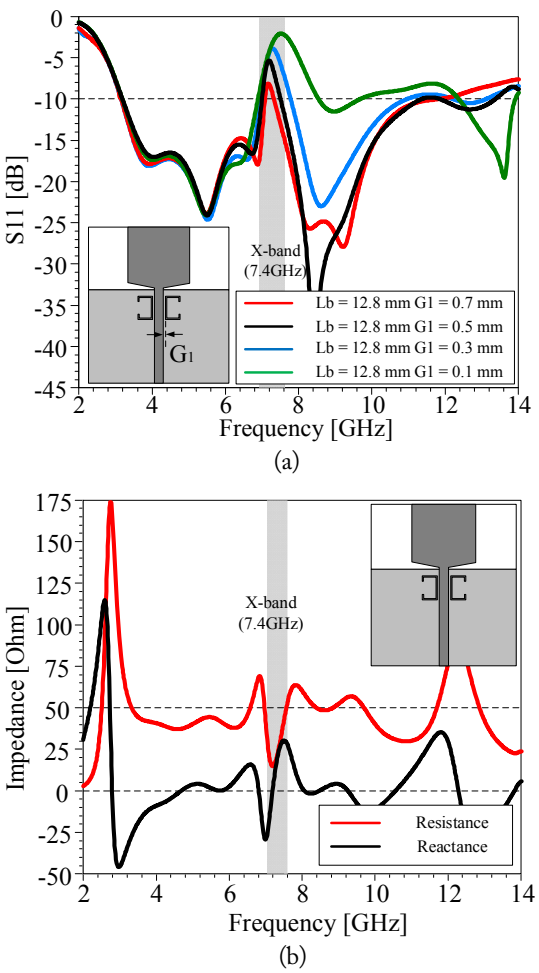


Fig. 7. S_{11} characteristics of (a) the single notch band (X-band) for various G_1 (L_b = 12.8 mm) and (b) input impedance of the proposed single notch band for the X-band.

Single Notch Band for ITU 8 GHz Signal Band

To reduce the unwanted ITU 8 GHz signal level, a single-notched band structure with a U-shaped band stop filter is applied to a trapezoid UWB antenna. The band-notched characteristic at the desired frequency can be obtained by adjusting the length of the filter L_d to be approximately a half wavelength and the gap G_2 between the filter and the transmission line. The influence of the four different lengths of the filter L_d with a constant gap $G_2 = 0.1$ mm is shown in Fig. 8(a). A wide notch band is obtained when L_d is changed from 10.0 mm to 11.6 mm. In consideration of the desired notch band performance for the ITU 8 GHz signal band, L_d is selected to be 10.8 mm. Fig. 8(b) shows the S_{11} characteristics for a gap G_2 varying from 0.2 mm to 0.8 mm with a constant length $L_d = 10.8$ mm. The band rejection level decreases when G_2 is larger than 0.2 mm. Thus, 0.2 mm is chosen for G_2 in the design. Fig. 8(d) shows the S_{11} characteristics of the single notch band (ITU 8 GHz band) for various L_e. In this work, 9.8 mm is chosen for L_e. With L_e increasing or decreasing, the bandwidth in ITU 8 GHz band is broadened, and the impedance matching in the high-frequency band deteriorates. In consideration of the wanted notched bandwidth in ITU 8 GHz band and impedance matching in the high-frequency band, 9.8 mm is chosen for the location of the U-shaped filter.

Fig. 8(e) shows the S_{11} characteristics of the single notch band with a U-shaped filter and with a pair of U-shaped filters for the ITU 8 GHz band. Although the rejection level improves in the case of the pair of U-shaped filters, the bandwidth in the ITU 8 GHz band exceeds the wanted notched bandwidth (800 MHz), and impedance matching in the high-frequency band deteriorates. In addition, the rejection level in the case of a single U-shaped filter satisfies the good rejection level in this design. Thus, in consideration of the proposed notched bandwidth and impedance matching in the high-frequency band, a single U-shaped filter is chosen in this work.

Fig. 8(c) shows the input impedance of the single band-notched antenna. At the central frequency of 8.4 GHz, the imaginary component curve exhibits a parallel resonant characteristic, and the real part peaks at around 120 Ω. The antenna cannot radiate efficiently at this frequency because of impedance mismatching.

Performance of the Proposed Antenna

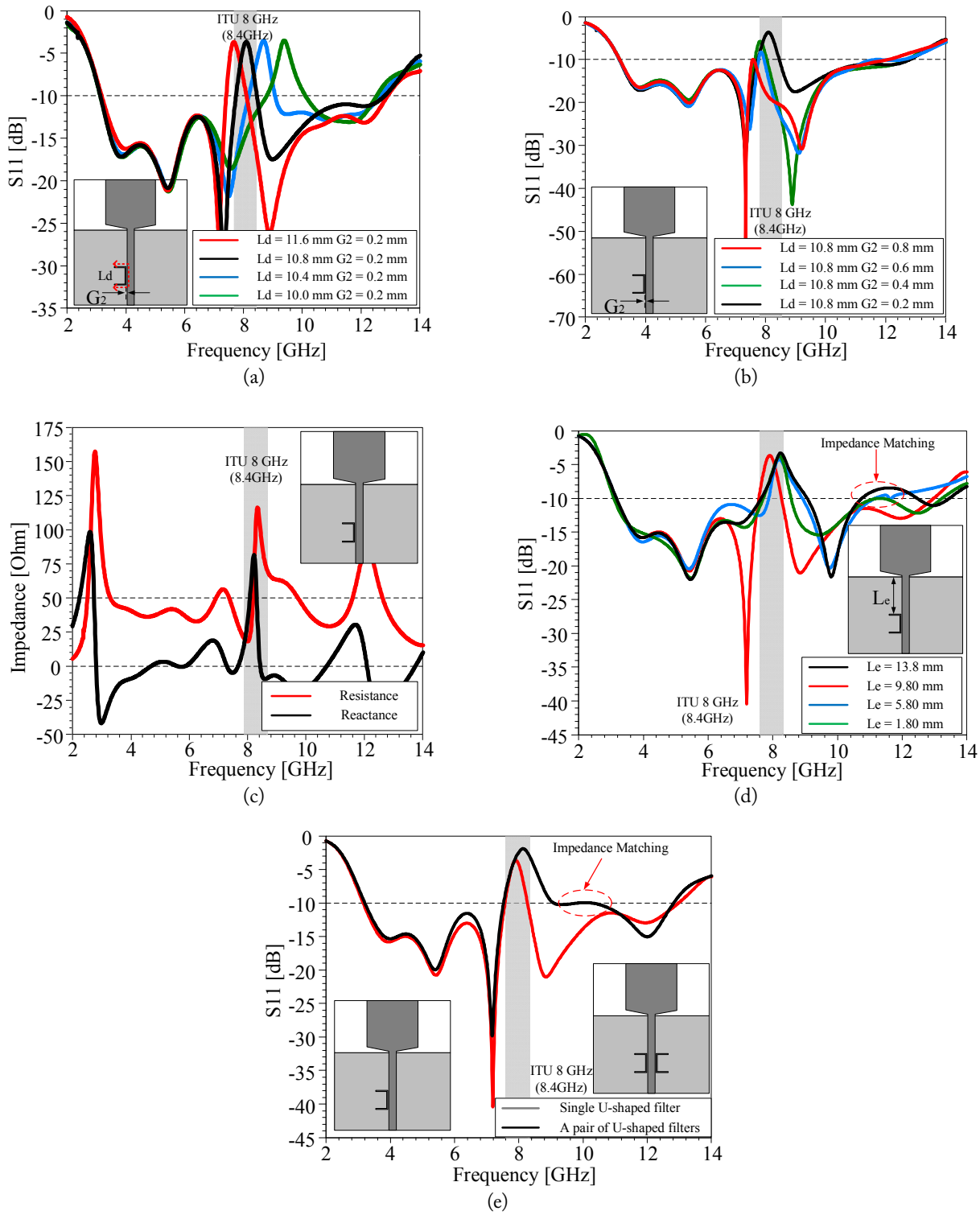


Fig. 8. Antenna configuration: (a) S_{11} characteristics of the single notch band (ITU 8 GHz) for various L_d (G_2 = 0.2 mm) and (b) various G_2 (L_d = 10.8 mm); (c) input impedance of the single notch band for ITU 8 GHz signal band; (d) S_{11} characteristics of the single notch band (ITU 8 GHz band) for various L_e; and (e) S_{11} characteristics of the single notch band with a U-shaped filter and with a pair of U-shaped filters for the ITU 8 GHz band.

The reflection coefficient characteristics in the previous subsections show that each notch band scheme generates a notch function in the designated frequency band only, and it does not affect the reflection coefficient characteristics in other notch bands. Thus, the quadruple notch band characteristic can be realized by combining the four notch struc-

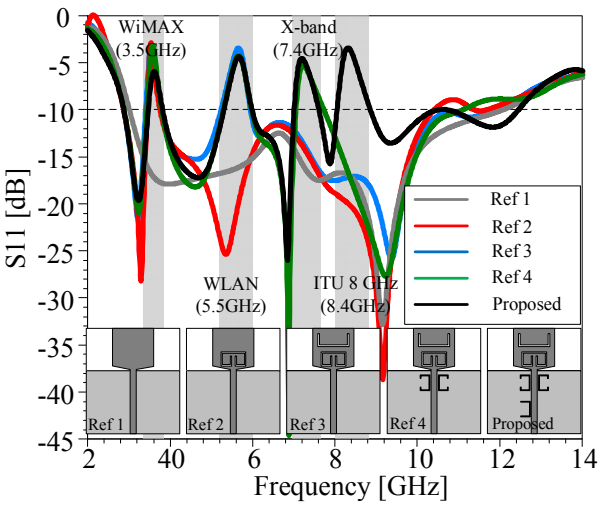


Fig. 9. S_{11} characteristics of several single-notched band structures and the proposed antenna.

tures mentioned in the previous subsections.

Fig. 9 presents the S_{11} characteristics of the single notch band antenna structures and the proposed antenna. Clearly, the corresponding band-notched characteristic in each structure is realized.

To further understand the operating principle behind this quadruple band-notched performance, the current distributions at four different notched frequencies are depicted in Fig. 10(a)–(d). The surface currents are highly concentrated near the edges of the slots and in the band rejection filters at the notch band frequencies. At these notch frequencies, energy is stored around the band-stop elements rather than being radiated into free space.

The measured and simulated peak gains of the proposed antenna are shown in Fig. 11(a). The peak gains at four

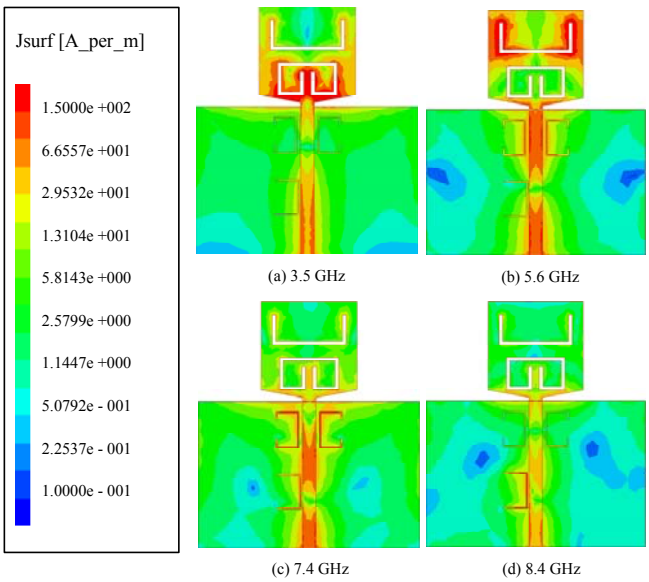
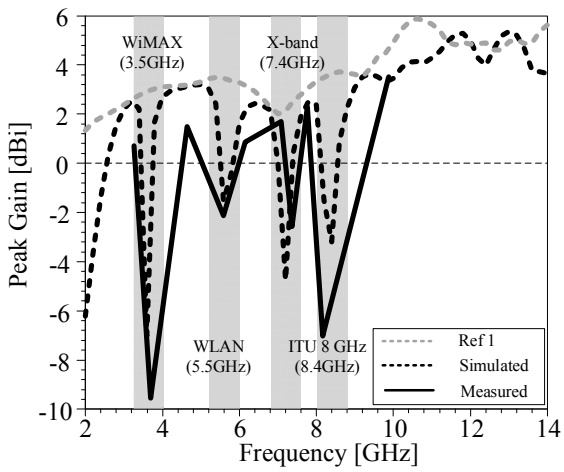
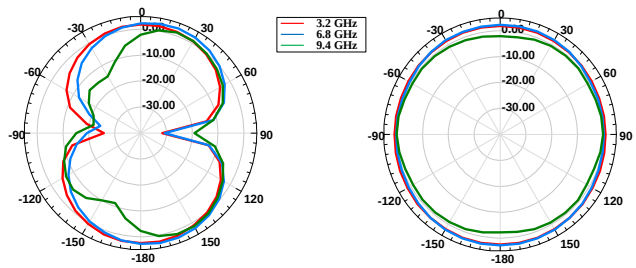


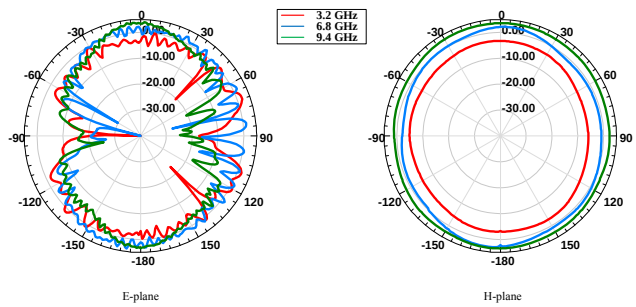
Fig. 10. Simulated surface current distribution in the notch bands of (a) 3.5 GHz, (b) 5.6 GHz, (c) 7.4 GHz, and (d) 8.4 GHz.



(a)



(b)



(c)

Fig. 11. Results of the (a) peak gain of the proposed antenna, (b) simulated radiation patterns, and (c) measured radiation patterns.

different notch bands are all smaller than 0 dBi. The peak gain performance of the proposed antenna is better than that found in previous research [16, 17]. One of the means to reduce the gains in a notch band is to improve the S_{11} or VSWR level of the notched bands in the proposed structure. The proposed antenna attains an average level of S_{11}, which is larger than −4.5 dB, in the notched bands. Therefore, the proposed antenna has good notch functions in this design.

Fig. 11(b) and (c) show the simulated and measured radiation patterns, respectively, of the proposed antenna in the E-plane and H-plane at 3.2, 6.8, and 9.4 GHz. The antenna shows omnidirectional radiation patterns in the H-plane.

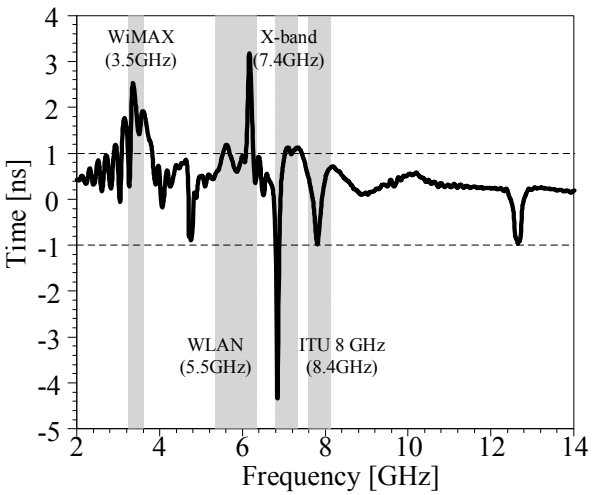


Fig. 12. Measured group delay of the fabricated antenna.

The measured group delay of the fabricated antenna is illustrated in Fig. 12. If the group delay variation exceeds 1 ns, the phases will not be linear in the far-field region. This condition causes pulse distortion bands, while the group delay variation exceeds 1 ns in the four desired notch bands. Based on the reflection coefficient, peak gain, and group delay characteristic results, the band-notched characteristic of the proposed antenna is well designed for UWB systems.

IV. Conclusion

In this paper, a trapezoid UWB antenna with a quadruple band-notched characteristic is proposed to avoid possible interference with the WiMAX, WLAN, X-band downlink, and ITU 8 GHz signal bands. The simulated reflection coefficient shows that the proposed antenna realizes a band-notched characteristic in the WiMAX (3.44–3.85 GHz), WLAN (5.26–6.01 GHz), X-band downlink (7.05–7.68 GHz), and ITU 8 GHz signal bands (8.08–8.87 GHz) by properly selecting the band rejection elements. The proposed antenna attains omnidirectional radiation patterns in the H-plane and has good peak gain performance at the notch bands. Therefore, the proposed antenna is a good candidate for UWB communication with band-notched applications.

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