Progress In Electromagnetics Research, Vol. 139, 303–315, 2013

A COMPACT QUAD BAND-NOTCHED UWB MONOPOLE ANTENNA LOADED ONE LATERAL L-SHAPED SLOT

Zi-Han Wu*, Feng Wei, Xiao-Wei Shi, and Wen-Tao Li

National Laboratory of Science and Technology on Antennas and Microwaves, Xidian University, Xi'an, Shaanxi 710071, China

Abstract—A novel compact microstrip-fed planar monopole antenna with quad-notched bands is presented. The proposed antenna is based on one rectangular-stepped-patch. To achieve the higher resonance over the 12 GHz, one lateral L-shaped structure is embedded in the ground. By inserting four U-shaped slots in the radiation patch, quad band-notched properties in the WiMAX (3.3–3.6 GHz), INSAT (4.5–4.8 GHz), lower WLAN (5.15–5.35 GHz) and higher WLAN (5.725–5.825 GHz) are obtained. Experimental results indicate that the designed UWB antenna can obtain broadband matched impedance values, good frequency selectivity over the notched bands, relatively flat group delay and nearly omni-directional transmission characteristics across the UWB frequencies. More importantly, the quad-notched bands can be reconfigurable by shorting the corresponding U-shaped slots.

1. INTRODUCTION

Since the Federal Communications Commission (FCC)'s decision to permit the unlicensed operation band from 3.1 to 10.6 GHz in 2002, the ultra-wideband (UWB) radio system has been getting increasingly popular from the academic and industry fields. As the key component of the UWB wireless communication system, the UWB antenna has drawn increasing attention [1–4]. The feasible UWB antenna should be designed with compact size, good impedance matching, flat group delay and omni-directional radiation patterns [5, 6]. However, a permanent challenge is that there are interferences between the designed UWB system and some overlapping frequency bands. To avoid the interferences, it is necessary to filter out the overlapping

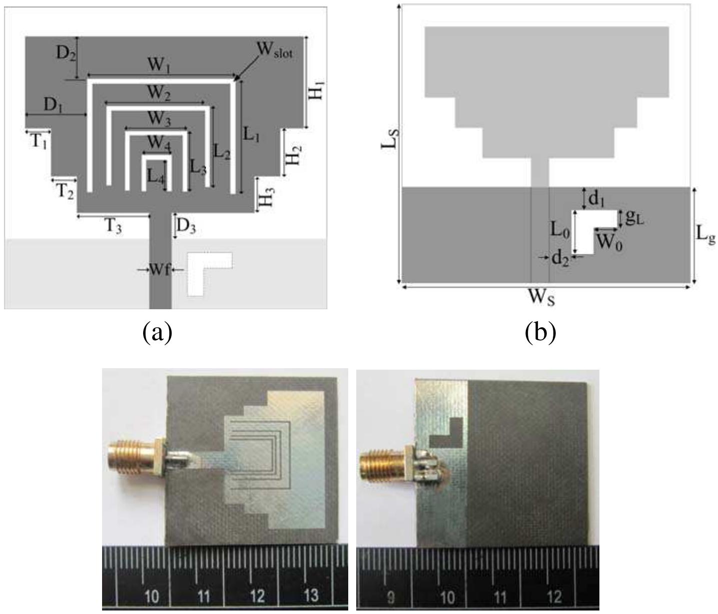
Received 27 February 2013, Accepted 15 April 2013, Scheduled 30 April 2013
* Corresponding author: Zi Han Wu (zihan_spring@163.com).

frequency bands. Since the approach to use filters applied to UWB RF front ends to reject dispensable bands may take too much space and leads to significant increase in the design complexity, UWB antennas with band-notched characteristic function to avoid potential inference have been put forward [7–9]. Though various UWB antennas with band-notched characteristic have been recently presented, most of which were designed with one notched band [10–12], two notched bands [13–17], or three notched bands [18–22] at the aforementioned frequency bands. In [23], a quad band-notched antenna is obtained based on a rectangular slot patch and closed-loop ring resonators on multilayered planes, but the radiation patterns is not omni-directional in the H-plane and the structure is too complex. Moreover, the mentioned UWB antennas only have fixed notched bands. The existing undesired narrowband radio signals vary from place to place and time to time. Therefore, it is more desirable to introduce reconfigurable notch bands. Besides, there are even configurable UWB antennas with band notches which can be achieved in different ways. Examples include switching on or off a MEMS or a PIN diode, tuning a varactor or using a PIN and a varactor together in the same UWB antenna [24–26]. However, most of these antennas have only one notch band around WLAN band. Moreover, some antennas occupy the entire 5–6 GHz frequency band which is much wider than needed (200 MHz for the lower WLAN band, 100 MHz for the upper WLAN band) [27].

In this paper, a quad band-notched antenna is proposed, which is obtained by integrating an antennas and some non-radiating resonant structures in the radiation patch. More importantly, the proposed notched bands can be reconfigured by shorting corresponding U-shaped slot. In the part 2.1 of Section 2, the method of practically realizing the proposed antenna performance reconfiguration is explained. Meanwhile a lateral L-shaped slot loading is employed in the ground-plane to obtain wider resonant band. Moreover, simulated and measured results in both frequency and time domain for this proposed antenna are also detailed in this section.

2. ANALYSIS AND DESIGN

Through simulation with the software Ansoft HFSS 13.0, the geometry and configuration of the final optimized antenna, being used as the base for the eventual multi-band antenna as shown in Fig. 1. This antenna was printed on the ROGERS 5880 substrate with a dimension of $30 \times 31 \times 1\,\mathrm{mm}^3$, relative dielectric constant of 2.2, and loss tangent of 0.0009. The width of the microstrip feed line is fixed at 3 mm to achieve $50\,\Omega$ characteristic impedance.



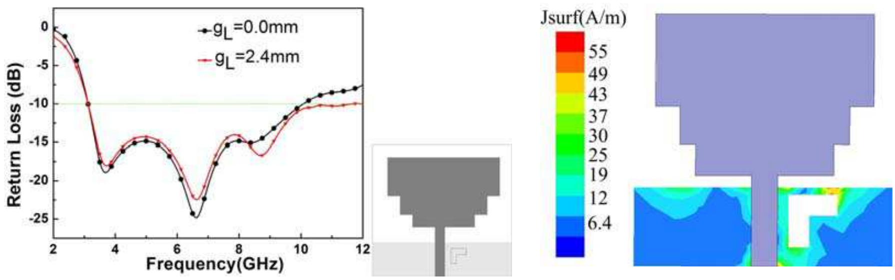
(a) (b)

(c)

Figure 1. Geometry of the proposed UWB antenna. (a) Top view, (b) bottom view, and (c) fabricated antenna. All dimensions are in mm: $W_S = 30\text{mm}$, $L_s = 31\,\text{mm}$, $L_g = 9\,\text{mm}$, $d_1 = 0.8\,\text{mm}$, $d_2 = 1.2\,\text{mm}$, $g_L = 2.4\,\text{mm}$, $L_0 = 6\,\text{mm}$ $W_0 = 3.2\,\text{mm}$, $W_f = 3\,\text{mm}$, $D_1 = 5.45\,\text{mm}$, $D_2 = 6.06\,\text{mm}$, $D_3 = 1.3\,\text{mm}$, $T_1 = 2.775\,\text{mm}$, $T_2 = 1.795\,\text{mm}$, $T_3 = 6.43\,\text{mm}$, $H_1 = 10.46\,\text{mm}$, $H_2 = 4.31\,\text{mm}$, $H_3 = 3.54\,\text{mm}$, $L_1 = 11\,\text{mm}$, $L_2 = 8.95\,\text{mm}$, $L_3 = 8.27\,\text{mm}$, $L_4 = 7.92\,\text{mm}$, $W_{slot} = 0.3\,\text{mm}$, $W_1 = 12.4\,\text{mm}$, $W_2 = 9\,\text{mm}$, $W_3 = 7.2\,\text{mm}$, $W_4 = 6\,\text{mm}$.

2.1. Basic UWB Antenna Design

In order to create the higher resonance, a lateral L-shaped structure is embedded in the ground as shown in Fig. 2(b). Fig. 2(a) shows the compared graph by varying the width g_L of the lateral L-shaped slot in the ground plane. Ultimately, the basic antenna (without any slots S_1, S_2, S_3, and S_4) covers the entire UWB band of 2.8–12 GHz (VSWR $<$ 2.0) with $g_L = 2.4\,\text{mm}$ It can be seen from Fig. 2(b) that the strong currents concentrate along the L-shaped slot on the ground-plane and wrap around it at 12 GHz. In this way, the L-shaped slot plays the role of coupling slots and couple energy to the free space. Therefore, 2 GHz bandwidth in the higher frequency band is broadened.



(a) (b)

Figure 2. (a) Simulated reflection coefficient of the basic antenna (without the notched region) with varied g_L and (b) current distribution on the conductors of the basic antenna loaded the lateral L-shaped slot at 12 GHz.

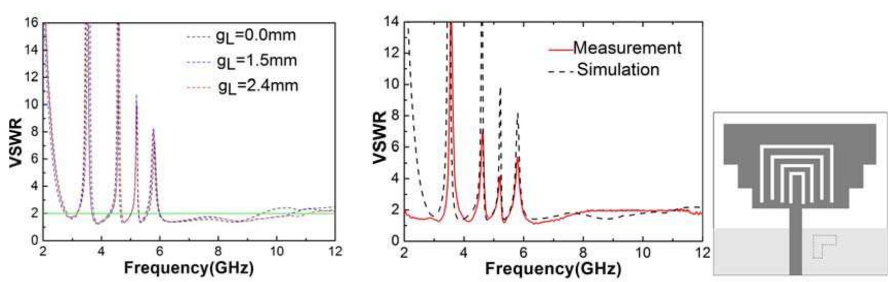
2.2. The Reconfiguration Analysis of U-shaped Slot

Each U-shaped slot can act as one half-wavelength resonator. The resonance frequency f_r of the slot can be derived as [18]

$$f_r = \frac{c}{2(L_N + W_N)}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

where L_N and W_N is the length and width of U-shaped slot. Therefore, the desired notch frequency can be achieved by adjusting the dimensions of the U-shaped slot.

The proposed UWB antenna consists of four U-shaped slots nested together to achieve four notched bands. It can be observed that g_L has a deterministic influence on the high frequency impedance matching, as shown in Fig. 3(a). With the increase of g_L, a better impedance



(a) (b)

Figure 3. (a) Simulated VSWR for the proposed antenna with varied g_L and (b) simulated and measured VSWR of the eventual optimized quad band-notched antenna with $g_L = 2.4$ mm.

matching can be obtained over the high frequency band. After the optimization of the dimensions of g_L, the final simulated and measured VSWR of the optimized quad band-notched antenna with $g_L = 2.4\,\text{mm}$ are shown in Fig. 3(b). The measurement was performed with an Agilent N5230A vector network analyzer. The antenna with four half-wavelength slots successfully exhibits four designed notched bands in 3.5–3.6, 4.5–4.8, 5.15–5.35 and 5.725–5.825 GHz, which maintain broadband performance from 2.8 to 11 GHz with VSWR less than 2, as shown in Fig. 3(b). Though there are some differences in terms of the value of VSWR being due to the fabrication accuracy on the width of the U-shaped slots, quite good agreement is obtained in terms of frequency.

Meanwhile, the quad band-notched UWB antenna can be reconfigurable by shorting the corner point of the single U-shaped slot and the corresponding notched band is removed with the remain band-notched frequency nearly invariable, as shown in Figs. 4(a)–(d). In addition, the different notch bands can be changed independently. The concrete realization method is to short the corners of the U-shaped-slot resonator by pasting metal film and welding resistances: such as 0 ohm resistance. The advantage of shorting elements in regard to removing the entire element from the layout is that it enables future

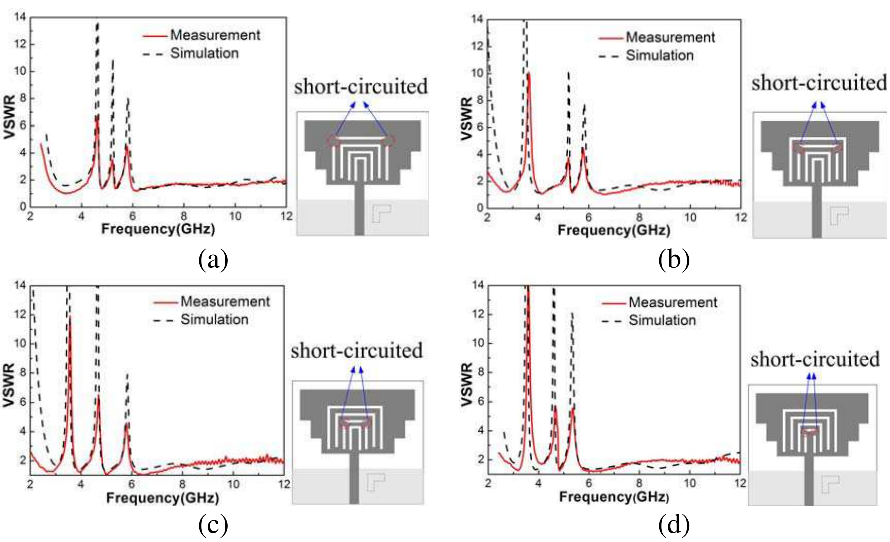


Figure 4. Simulated and measured VSWR of the band- notched antenna by shorting the notch frequency at (a) 3.5 GHz, (b) 4.6 GHz, (c) 5.2 GHz, and (d) 5.8 GHz.

printing techniques to preserve the layout with all the other U-shaped slots invariant.

The surface current distributions of the proposed quad band-notched antenna at frequencies of 3.5, 4.6, 5.2 and 5.8 GHz are shown in Figs. 5(a)–(d). It can be seen that the currents mainly concentrate over the corresponding U-shaped slot at 3.5, 4.6, 5.2 and 5.8 GHz. For the four cases, corresponding interference will be destructed. As shown in Figs. 6(a)–(d), by shorting the corresponding notched band, the effect of the half-wavelength resonator disappears. Despite the presence of some weakly coupling, it will be of no significance.

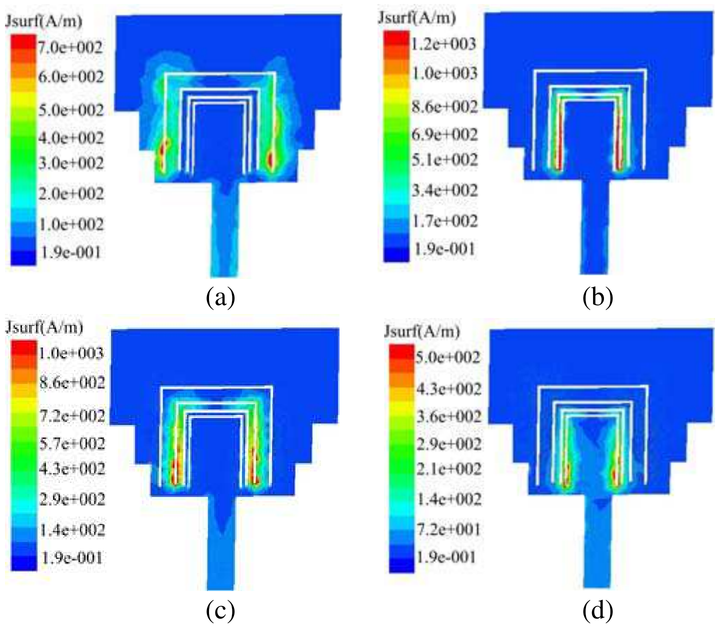


Figure 5. Current distribution on the conductors of the band-notched antenna at (a) 3.5 GHz, (b) 4.6 GHz, (c) 5.2 GHz and (d) 5.8 GHz.

3. RESULTS AND DISCUSSION

Finally, the proposed quad band-notched UWB antenna is measured with Satimo SG24. Fig. 7 displays the simulated and measured far-field radiation patterns at 3.1, 5 and 7 GHz, which show good agreement. Since the radiating element is printed on the xy-plane, of which monopole lies along the x-direction, its radiation pattern is x-polarized. Therefore, the E-plane corresponds to the xz-plane, while the H-plane

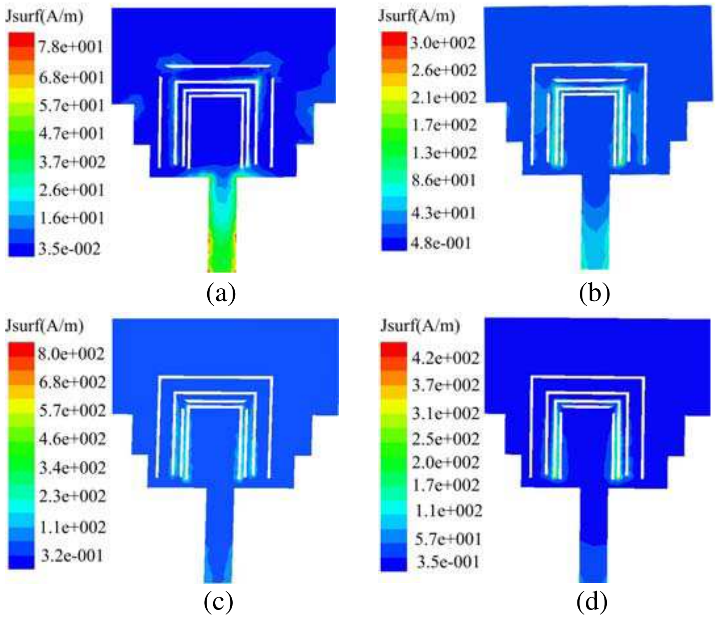


Figure 6. Current distribution on the conductors with the notched band shorted at (a) 3.5 GHz, (b) 4.6 GHz, (c) 5.2 GHz and (d) 5.8 GHz, respectively.

corresponds to yz-plane. As shown in Fig. 7, the proposed quad band-notched antenna has characteristics of nearly omni-directional radiation patterns in the H-plane and monopole-like patterns in the E-plane [28].

The measured maximum gain of the antenna is depicted in Fig. 8. Four sharp reductions at the desired four notch frequency at 3.5, 4.6, 5.2 and 5.8 GHz clearly confirm the signal-rejection capability of the proposed antenna. The notched bands have high selectivity (−10-dB FBW are 13.7%, 10.8%, 5.6% and 8.1%, respectively). In order to verify the good capability of the proposed quad band-notched antenna in the UWB system, it is desired to achieve a stable group delay. The group delay is measured between two identical antennas in the face-to-face orientations, with a distance of 0.6 m between them. As presented in Fig. 9(a), the measured group delay is fairly stable except the notched frequency bands.

In designing band-notched UWB antenna, besides the frequency domain characteristics, the time-domain characteristics are significant criteria to estimate the performance of band-notched UWB antenna. So, in this section, group delay and waveform responses are performed

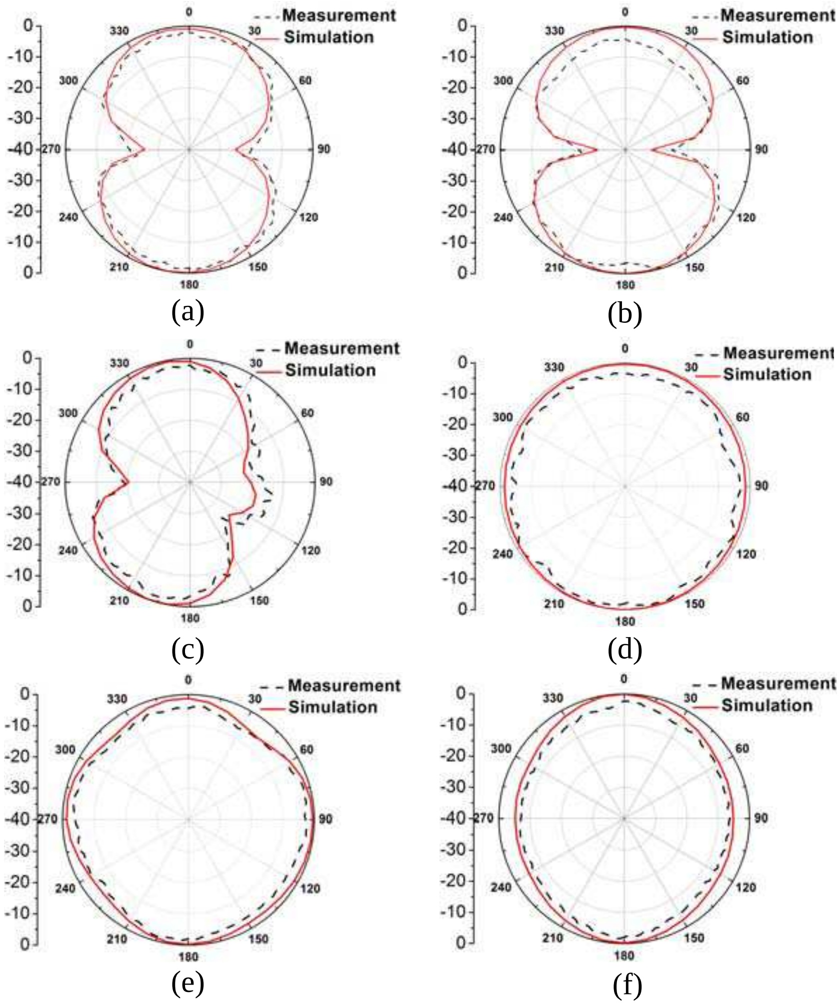


Figure 7. E-plane radiation pattern of the quad-band antenna at various frequencies of (a) 3.1 GHz, (b) 5 GHz, and (c) 7 GHz and H-plane radiation pattern of the quad-band antenna at various frequencies of (d) 3.1 GHz, (e) 5 GHz, and (f) 7 GHz.

to evaluate time-domain characteristics of the proposed antennas. As presented in Fig. 9, stable group delay and fairly flat magnitude of the transfer function are achieved for the proposed antenna, except the notched frequency bands.

To evaluate time delay, duration and distortion of the pulse

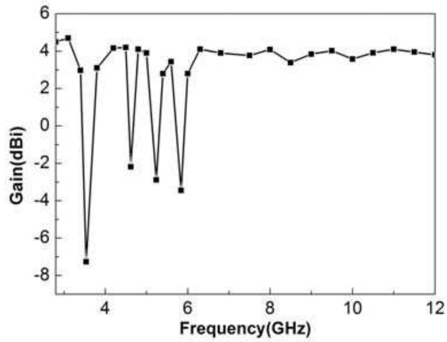


Figure 8. Measured maximum gain of the quad band-notched UWB antenna.

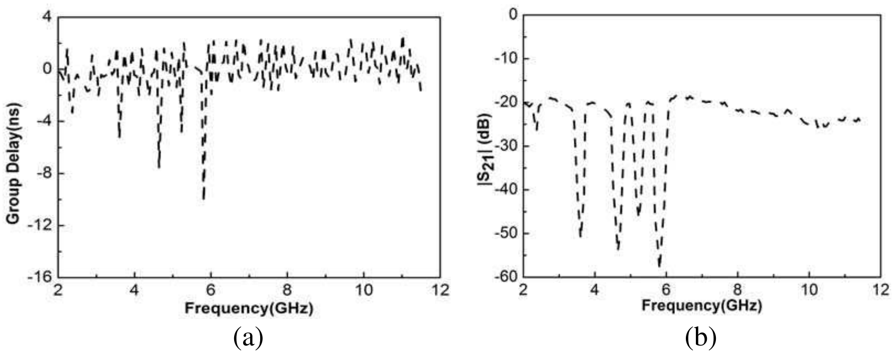


Figure 9. (a) The group delay and (b) transmission characteristic of the quad band-notched UWB antenna.

waveform during the transient transmission, the proposed antenna is assumed to be excited by the UWB signal as in [29], which satisfies the FCC spectral mask for indoor systems given by:

$$u(t) = \cos(2\pi f_c t) \exp\left[-2\pi(t/\tau)^2\right] \quad (2)$$

Here, f_c and τ take the same values as in [29]. The input signal with pulse shape is displayed as the solid curve in Fig. 10.

To obtain the received pulse at the other antenna, the measured S_{21} shown in Fig. 9 is employed. The output pulse, as the dotted curve in Fig. 10 for comparison, is shifted backward in time to eliminate the overlap with input pulse due to the small separation (0.6 m) between the transmitting and receiving antennas and the pulse duration (or risetimes) is 91 ps. In order to quantify the pulse distortion, two figures of merit referring to the correlation factor and the pulse width

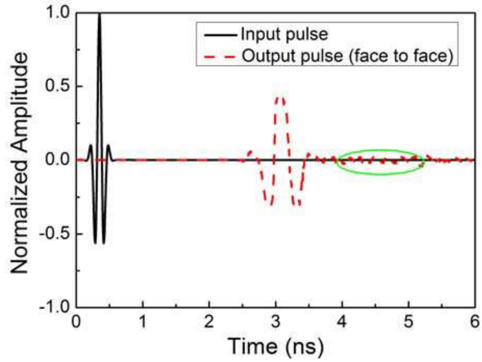


Figure 10. Shifted and normalized input and output pulse in time-domain for a UWB link with two identical face-to-face antennas.

stretch ratio SR are introduced. They could be calculated between the input signal at the transmitting antenna terminal and the signal at the receiving antenna terminal by using transmission characteristics of the proposed antennas. Their measured results are $\rho = 0.9023$ and SR $= 3.1$ [29–32], respectively. From Fig. 10, we can see that not all the energy is concentrated in the vicinity of the peak, and a little noise energy deviated from the peak introduces the ringing distortion which introduced by antenna characteristics of rejection bands. So, the proposed antenna will introduce little distortion on signals during the UWB pulse transmission and the receiving antenna signals will be not distorted seriously compared with the input signal.

4. CONCLUSION

A planar quad band-notched monopole antenna is proposed for UWB band applications. Meanwhile, by etching four U-shaped-slot resonators in the radiation patch, four reconfigurable notched bands can be achieved. Because of its simple structure, compact size, stable omni-directional radiation patterns and relatively consistent group delay across the whole radiating frequency bands, the proposed antenna is attractive for use in future UWB wireless technologies.

ACKNOWLEDGMENT

This work was supported by the Fundamental Research Funds for the Central Universities (K50511020013) and the National Natural Science Foundation of China under Grant 61101069.

REFERENCES

1. Xu, H.-Y., H. Zhang, K. Lu, and X.-F. Zeng, "A holly-leaf-shaped monopole antenna with low RCS for UWB application," *Progress In Electromagnetics Research*, Vol. 117, 35–50, 2011.
2. Saleem, R. and A. K. Brown, "Empirical miniaturization analysis of inverse parabolic step sequence based UWB antennas," *Progress In Electromagnetics Research*, Vol. 114, 369–381, 2011.
3. Chen, D. and C. H. Cheng, "A novel compact ultra-wideband (UWB) wide slot antenna with via holes," *Progress In Electromagnetics Research*, Vol. 94, 343–349, 2009.
4. Andres-Garcia, B., L. E. Garcia-Munoz, D. Segovia-Vargas, I. Camara-Mayorga, and R. Gusten, "Ultrawideband antenna excited by a photomixer for terahertz band," *Progress In Electromagnetics Research*, Vol. 114, 1–15, 2011.
5. Fan, S.-T., Y.-Z. Yin, H. Li, and L. Kang, "A novel self-similar antenna for UWB applications with band-notched characteristics," *Progress In Electromagnetics Research Letters*, Vol. 22, 1–8, 2011.
6. Ray, K. P. and S. Tiwari, "Ultra wideband printed hexagonal monopole antennas," *IET Microw. Antennas Propag.*, Vol. 4, Issue 4, 437–445, 2010.
7. Lee, W.-S., K.-S. Oh, and J.-W. Yu, "A wideband planar monopole antenna array with circular polarized and band-notched characteristics," *Progress In Electromagnetics Research*, Vol. 128, 381–398, 2012.
8. Azim, R. and M. T. Islam, "Compact planar UWB antenna with band notch characteristics for WLAN and DSRC," *Progress In Electromagnetics Research*, Vol. 133, 391–406, 2013.
9. Deng, J. Y., Y. Z. Yin, S. G. Zhou, and Q. Z. Liu, "Compact ultra-wideband antenna with tri-band notched characteristic," *Electron. Lett.*, Vol. 44, No. 21, 1231–1233, Oct. 2008.
10. Thomas, K. G. and M. Sreenivasan, "A simple ultrawideband planar rectangular printed antenna with band dispensation," *IEEE Trans. on Antennas and Propag.*, Vol. 58, No. 1, 27–34, Jan. 2010.
11. Liu, H. W., C. H. Ku, T. S.Wang, and C. F. Yang, "Compact monopole antenna with band-notched characteristic for UWB applications," *IEEE Antennas Wireless Propag. Lett.*, Vol. 9, 397–400, 2010.
12. Vuong, T. P., A. Ghiotto, Y. Duroc, and S. Tedjini, "Design and characteristics of a small U-slotted planar antenna for IR-UWB,"

Microw. Opt. Technol. Lett., Vol. 49, No. 7, 1727–1731, Jul. 2007.
13. Li, C.-M. and L.-H. Ye, "Improved dual band-notched UWB slot antenna with controllable notched bandwidths," *Progress In Electromagnetics Research*, Vol. 115, 477–493, 2011.
14. Abdollahvand, M., G. Dadashzadeh, and D. Mostafa, "Compact dual band-notched printed monopole antenna for UWB application," *IEEE Antennas Wireless Propag. Lett.*, Vol. 9, 1148–1151, 2010.
15. Zhang, G.-M., J.-S. Hong, and B.-Z. Wang, "Two novel band-notched UWB slot antennas fed by microstrip line," *Progress In Electromagnetics Research*, Vol. 78, 209–218, 2008.
16. Liu, H. W., C. H. Ku, and C. F.Yang, "Novel CPW-fed planar monopole antenna for WiMAX/WLAN applications," *IEEE Antennas Wireless Propag. Lett.*, Vol. 9, 240–243, 2010.
17. Zhu, F., S.-C. S. Gao, A. T. S. Ho, C. H. See, R. A. Abd-Alhameed, J. Li, and J.-D. Xu, "Design and analysis of planar ultra-wideband antenna with dual band-notched function," *Progress In Electromagnetics Research*, Vol. 127, 523–536, 2012.
18. Mohammadian, N., M. N. Azarmanesh, and S. Soltani, "Compact ultra-wideband slot antenna fed by coplanar waveguide and microstrip line with triple-band-notched frequency function," *IET Microw. Antennas Propag.*, Vol. 4, Issue 11, 1811–1817, 2010.
19. Islam, M. T., R. Azim, and A. T. Mobashsher, "Triple band-notched planar UWB antenna using parasitic strips," *Progress In Electromagnetics Research*, Vol. 129, 161–179, 2012.
20. Liu, J., K. P. Esselle, S. G. Hay, and S.-S. Zhong, "Study of an extremely wideband monopole antenna with triple band-notched characteristics," *Progress In Electromagnetics Research*, Vol. 123, 143–158, 2012.
21. Trang, N. D., D. H. Lee, and H. C. Park, "Design and analysis of compact printed triple band-notched UWB antenna," *IEEE Antennas Wireless Propag. Lett.*, Vol. 10, 403–406, 2011.
22. Li, G., H. Zhai, T. Li, X. Y. Ma, and C.-H. Liang, "Design of a compact UWB antenna integrated with GSM/WCDMA/WLAN bands," *Progress In Electromagnetics Research*, Vol. 136, 409–419, 2013.
23. Almalkawi, M. J. and V. K. Devabhaktuni, "Quad band-notched UWB antenna compatibl with WiMAX/INSAT/lower-upper WLAN applications," *Electron. Lett.*, Vol. 47, No. 19, Sep. 2011.
24. Sim, C.-Y.-D., W.-T. Chung, and C.-H. Lee, "Planar UWB

antenna with 5 GHz band rejection switching function at ground plane," *Progress In Electromagnetics Research*, Vol. 106, 321–333, 2009.

25. Xu, F., L. Tang, X. Chen, and X.-A. Wang, "Active UWB printed antenna with tuanble and switchable band-notched functions," *Progress In Electromagnetics Research Letters*, Vol. 30, 21–28, 2012.
26. Dissanayake, T. and K. P. Esselle, "Prediction of the notch frequency of slot loaded printed UWB antennas," *IEEE Trans. on Antennas and Propag.*, Vol. 55, No. 11, Nov. 2007.
27. Xu, F., Z. X. Wang, X. Chen, and X.-A. Wang, "Dual band-notched UWB antenna based on spiral electromagnetic-bandgap structure," *Progress In Electromagnetics Research B*, Vol. 39, 393–409, 2012.
28. Kim, D.-O., N.-I. Jo, H.-A. Jang, and C.-Y. Kim, "Design of the ultrawideband antenna with a quadruple-band rejection characteristics using a combination of the complementary split ring resonators," *Progress In Electromagnetics Research*, Vol. 112, 93–107, 2011.
29. Costa, J. R., C. R. Medeiros, and C. A. Fernandes, "Performance of crossed exponentially tapered slot antenna for UWB systems," *IEEE Trans. on Antennas and Propag.*, Vol. 57, No. 5, 1345–1352, May 2009.
30. Peng, L. and C. L. Ruan, "Design and time-domain analysis of compact multi-band-notched UWB antennas with EBG strictures," *Progress In Electromagnetics Research B*, Vol. 47, 339–357, 2013.
31. Yang, Y.-Y., Q.-X. Chu, and Z.-A. Zheng, "Time domain characteristics of band-notched ultrawideband antenna," *IEEE Trans. on Antennas and Propag.*, Vol. 57, No. 10, Oct. 2009.
32. Lizzi, L., G. Oliveri, and A. Massa, "A time-domain approach to the synthesis of UWB antenna systems," *Progress In Electromagnetics Research*, Vol. 122, 557–575, 2012.