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RESEARCH PAPER

Novel wideband slot antenna having notch-band function for 2.4 GHz WLAN and UWB applications

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In this paper, the design, simulation, and fabrication of a novel printed rectangular slot antenna with a band-notched function suitable for 2.4 GHz wireless local area network (WLAN) and ultra-wideband (UWB) applications is presented and investigated. Two pairs of slits are introduced into the ground plane to realize band-notched function, by tuning the position, length, and width of which a suitable rejected frequency band can be obtained. To improve the impedance matching, a rectangular cut is also made in the ground plane so that the antenna can cover 2–12 GHz frequency range. According to the measured results, the proposed antenna has a large bandwidth totally satisfying the requirement of 2.4 GHz WLAN and UWB systems, while providing the required band-notch function from 5.1 to 5.9 GHz. The study of transfer function and time-domain characteristics also indicates the band-notched function of the antenna. The radiation patterns display nearly omni-directional performance and the antenna gain is stable except in the rejected frequency band (5.1–5.9 GHz). Moreover, group delays are within 1.5 ns except for the notch band. These features make it a promising candidate for UWB wireless applications. Details of this antenna are described, and the experimental results of the constructed prototype are given.

Keywords: Slot antenna, WLAN/UWB operation, Notch band, Rectangular cut, Time-domain characteristic

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I. INTRODUCTION

Ultra wideband (UWB) technology has drawn more and more attention in wireless communication systems, particularly in wireless multimedia systems. It has many advantages over conventional wireless communication technology such as low power consumption, high-speed transmission, and simple hardware configuration in communication applications. One of the main issues in UWB communication systems is the design of a compact antenna, while providing wideband characteristics over the whole UWB range of frequencies. In 2002, the Federal Communication Commission (FCC) issued a ruling for UWB implementation in data communication [1]. According to it, a UWB antenna should provide a gain and impedance bandwidth from 3.1 to 10.6 GHz. Therefore, a variety of shapes and designs of UWB antennas have been studied. Several shapes such as diamond [2], ring [3], bow-tie [4], spline [5], elliptical [6], and square shapes [7] have been proposed to satisfy UWB specifications. In these antennas, several bandwidth enhancement techniques are used to have a continuous UWB bandwidth. A few attempts have been made to increase the bandwidth of Co Planar Waveguide (CPW)-fed slot antennas including a wide rectangular slot [8], a bow-tie slot [9], and some other broadband designs such as using a patch element loaded in a circular slot [10], a diamond patch in a rectangular slot [11], and a triangular patch in a rectangular slot [12]. Nevertheless, over the allocated UWB frequency band, there are existing wireless local area network (WLAN) bands such as 5.15–5.825 GHz bands, which might interfere with UWB operations, since the frequency range for UWB systems approved by the FCC is from 3.1 to 10.6 GHz. In order to avoid potential distortion of the 5 GHz WLAN system, a notch filter in the UWB system is necessary. But, the use of a filter will increase the complexity and cost of the UWB system. Therefore, a UWB antenna having frequency band-notched characteristics is an alternative to overcome this problem. To achieve frequency-rejected characteristic, many techniques are used including an embedded inverted U-shape [13], an embedded two slit on a circular monopole [14], adjusting a V-shaped thin slot length on the bow-tie shape slot antenna [15], and an embedded U-shape on a beveling rectangular patch [16]. A compact CPW-fed UWB antenna with band-notched characteristic has also been studied [17]. In this study, a tuning stub is inserted in the middle of the fork-like patch to achieve the band rejection characteristic. Another compact antenna study has a C-shaped slot to obtain the band-rejection operation of the antenna [18]. In [19], a

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slot-type split-ring resonator is inserted into the center line of the CPW to notch the WLAN frequency band.

Nowadays, it is often desired to design a wideband antenna with notch-band function, which can be used for multifunctional wireless communication systems like 2.4 GHz WLAN and UWB systems. A compact slot antenna for 2.4 GHz/UWB has been reported [20]. But, the antenna is designed for dual band-notched characteristic. Of the above studies, some antennas are fed with microstrip feed lines and some other antennas are excited with CPW feed lines. When an antenna is fed by a microstrip line, misalignment error can result because etching is required on both sides of the dielectric substrate. The alignment error can be eliminated if a CPW feed is used to excite the antenna, since etching of the slot and the feeding line is one sided. Furthermore, most of these antennas possess the lowest operating frequency at about 3 GHz, which makes them not suitable for applications in 2.4 GHz WLAN (2.4–2.484 GHz) systems. A wideband CPW-fed slot antenna designed for 2.4 GHz WLAN and UWB bands with a 5 GHz notched band is still rarely studied.

In this paper, a wideband CPW-fed rectangular slot antenna with a 5 GHz notch band for applications in 2.4 GHz WLAN and UWB systems is proposed. To produce a band-notched operation covering the 5 GHz WLAN band, two pairs of slits are introduced into the ground plane. By using a rectangular cut along with the slits in the ground plane, a broad impedance bandwidth (2–12 GHz) with notch band can easily be obtained.

II. ANTENNA STRUCTURE

Figure 1 shows the geometry of the reference antenna without the notch-band function. Figure 2 shows the structure and dimensions of the proposed rectangular slot antenna with the notch-band function, which is printed on an inexpensive FR4 substrate with a dielectric constant of $\epsilon_r = 4.4$ and substrate thickness of $h = 1.0$ mm. This slot antenna has a simple structure with one layer of dielectric and metal.

A co-ordinate system (x, y, and z) is oriented such that the bottom surface of the substrate in Fig. 2 lies on the y–z plane. The main structure of the proposed slot antenna has a wide

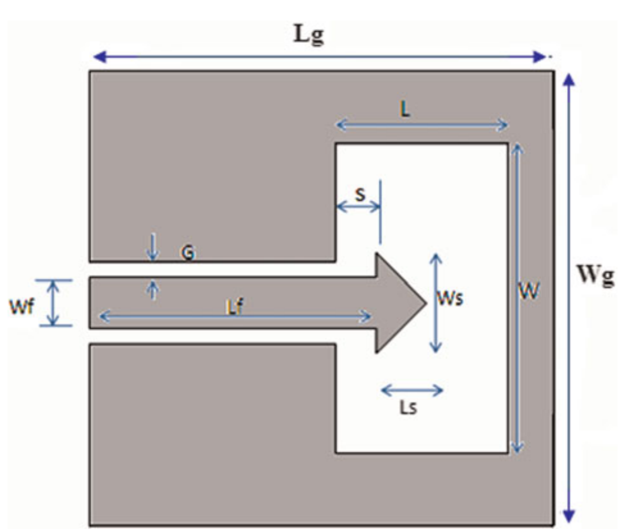

Fig. 1. Geometry of the reference antenna (units in mm).

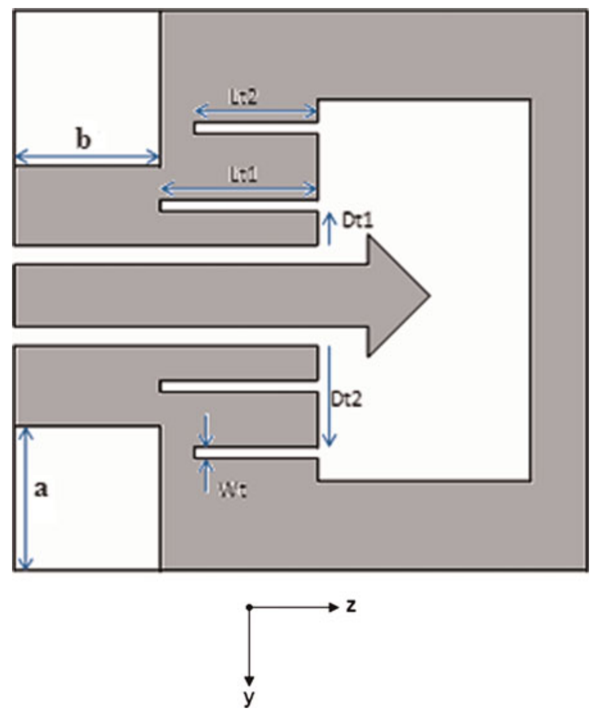

Fig. 2. Geometry of the proposed antenna (units in mm).

rectangular slot size of L mm × W mm and the dimension of the dielectric substrate is L_g mm × W_g mm. The antenna shape and its dimensions were first searched by using the ADS software and then the optimal dimensions were determined from experimental adjustment. In the design, wide rectangular slot is preferred because it offers wide bandwidth required for UWB applications. The antenna is excited by a CPW feed with a triangular-shaped tuning stub and the co-planar waveguide is designed to be 50 Ω in order to match the characteristic impedance of the transmission line. "G" is the gap distance between the metal strip and the co-planar ground plane. For perfect impedance matching with characteristic impedance of the 50 Ω transmission line, the gap (G), width of the center strip (W_f mm), and the length of CPW line (L_f mm) are designed to be 0.5, 2.8, and 16.9 mm, respectively. The triangular-shaped tuning stub is used at the center of the rectangular slot to enhance the coupling between the rectangular slot and the feed line. "L_s" is the length of the tuning stub and "W_s" is its width. Moreover, the center strip of the CPW feed is protruded into the rectangular slot up to the tuning stub. "S" is the spacing between the tuning stub and the ground plane. The present proposed antenna with good impedance matching can be implemented only when the spacing "S" is less than or equal to 2 mm [21], and the optimal spacing is found to be about 1.9 mm for enhancing the coupling between the stub and the ground plane. In fact, the dimensions of the rectangular slot (W and L), the parameters of the tuning stub (W_s and L_s), and the spacing (S) affect the broad-band operation of the slot antenna. By optimizing the value of W, L, W_s, and L_s, the antenna will cover the entire UWB range of frequencies [22]. The optimized values of the parameters (reference antenna) provide the widest bandwidth from 2.8 to 11.8 GHz as shown in Fig. 4(a).

To implement the band-notched characteristic for 5 GHz WLAN, we introduced one pair of slits into ground plane to produce a rejected band at the higher frequency and another pair of slits to produce a rejected band at the lower frequency. The slits are arranged symmetrically with respect to the feed line as shown in Fig. 2. The design concept of the band-notched function is to adjust the length, width, and position of the slit lines to be about half-wavelength at the desired notched frequency making the input impedance singular [23]. When the total length of the slits is set to be about a half-wavelength at center of the desired rejected frequency band, a narrow frequency band can be filtered out while maintaining good impedance matching over the rest of the UWB band from 2.5 to 11.8 GHz. Indeed, the slits introduced destroy the surface current on the ground so that the antenna becomes non-responsive at the notched frequency. Therefore, the slits decrease the current distribution at the notch-band frequency, reduce antenna's radiation capability, and eliminate unwanted band giving maximum attenuation.

In the parameter study, the first pair of slits is fixed in position at $D_{t1} = 1.6$ mm and its length (L_{t1}) and width (W_t) are adjusted to produce the band-notch function. Fine tuning of the notch band is effected with the introduction of the second pair of slits into the ground plane. Its location (D_{t2}) and length (L_{t2}) are adjusted to fine tune the notched band. But, the impedance bandwidth of the antenna is not capable of covering the 2.4 GHz WLAN band. Therefore, to reduce the overall size of the proposed antenna and obtain better impedance matching, rectangular cuts of ($a \times b$) mm^2 are symmetrically made in the ground plane. The side "b" of the rectangular cut is varied keeping the side "a" constant to cover the impedance band width from 2 to 12 GHz. Hence, a rectangular cut in the ground plane along with the slits is the basis of the proposed antenna. A prototype of the proposed antenna is fabricated and the reference antenna without slits is also constructed. The photographs of the proposed and reference antennas are shown in Fig. 3. The detailed dimensions of both the proposed and reference antennas are presented in Table 1.

III. RESULT AND DISCUSSION

The UWB behavior of the antenna is well known by a parametric study. The antenna shape and dimensions were studied by using the momentum software package of the advanced design system software [24], which is based on the method of moments and CST microwave studio which is based on the method of finite integration technique . The measurement was carried out with HP8722ES vector network analyzer after fabrication. To verify the proposed design, a prototype of the antenna based on optimized dimensions has been fabricated, as shown in Fig. 3. The measured and simulated Voltage Standing Wave Ratio (VSWR) against frequency for the proposed antenna are plotted and compared in Fig. 4(a). Result of the reference antenna without notch-band characteristics is also shown for comparison. As shown in this figure, the proposed rectangular slot antenna yields a wide bandwidth ranging from 2 to 12 GHz for VSWR less than 2, which covers the 2.4 GHz WLAN and the UWB bands except for the notched band from 5.1 to 5.9 GHz. This is also derived from the simulated input impedance curve on Smith chart [Fig. 4b]. Hence, basic agreements are achieved between the simulated result and the measured one. The differences between them may be caused by the soldering effects of an Sub-Miniature A (SMA) connector. The SMA connector is not accounted for in the simulation but is used in the experiment so that a varying reactance is loaded, leading to the movement of resonant points.

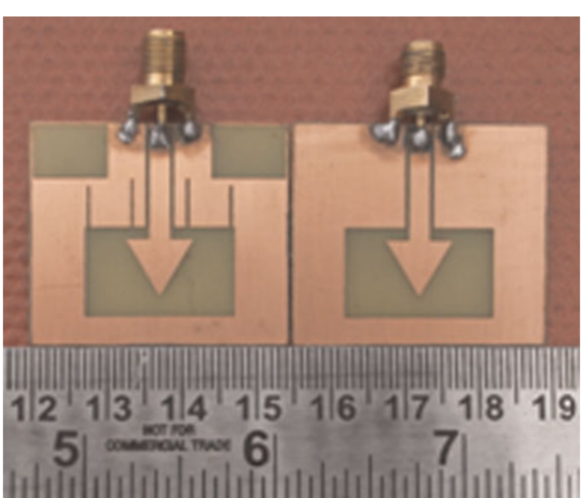

Fig. 3. Photograph of the proposed and reference antennas.

A) Parameters study

Figure 5(a) shows the simulated VSWR curves of the presented antenna with various slit lengths L_{t1}. As demonstrated in the figure, it is clear that the center frequency of the notched band is controlled by the length of the slit. As L_{t1} increases, the center frequency of the notched band shifts toward the lower frequency. With the increasing of L_{t1} from 6.5 to 7.5 mm, the center frequency shifts from 5.9 to 5.11 GHz. Figure 5(b) exhibits the effect of the various slit widths W_t on VSWR curves. It is apparent that the width of the slit W_t also has an effect on the rejected frequency. The center frequency shift from 5.7 to 5.2 GHz corresponds to the change of the slot width from 0.3 to 0.5 mm. Also, the lower edge of the notch band is shifted with negligibly small change than in the higher edge. The phenomenon means that W_t has a less effect comparing with L_{t1} on the rejected frequency. Moreover, both L_{t1} and W_t affect the notch bandwidth as well. When L_{t1} is equal to 7 mm and W_t is optimized at 0.4 mm, a notched band centered at 5.5 GHz is obtained. But, the notch-band covered is from 4.8 to 6.3 GHz.

In order to fine tune the notched band around the center frequency 5.5 GHz covering from 5.1 to 5.9 GHz, the influence of position and length of the second pair of slits along with the first pair is investigated. Accordingly, when the position of the second pair of slits D_{t2}, from the first pair of slits is increased, the center frequency of the notch band shifts toward the lower frequency with the reduction in the notch band covered. Finally, the length L_{t2} of the second pair of slits is varied to obtain the required notch band. When L_{t2} is 6 mm, the notch band is from 5.1 to 5.9 GHz. In all the above parameters study (L_{t1}, W_t, D_{t2}, and L_{t2}), one parameter is varied keeping the other parameters constant as shown in Table 1. Hence, it can be concluded that the rejected band can easily be obtained by tuning the parameters of the slits introduced into the ground plane. The optimal value is $L_{t1} = 7$ mm, $W_t = 0.4$ mm, $L_{t2} = 6$ mm, and $D_{t2} = 8.3$ mm, which have been obtained after performing an optimization

Table 1. Detailed dimensions of both the proposed and reference antennas.

Parameters	*Lg*	*Wg*	*L*	*W*	*Lf*	*Wf*	*G*	*S*
mm	32	34	13	22	16.9	2.8	0.5	1.9
(in λ_o)*	$0.213\lambda_o$	$0.23\lambda_o$	$0.09\lambda_o$	$0.15\lambda_o$	$0.113\lambda_o$	$0.02\lambda_o$	$0.003\lambda_o$	$0.013\lambda_o$
	$1.28\lambda_o$	$1.36\lambda_o$	$0.52\lambda_o$	$0.88\lambda_o$	$0.68\lambda_o$	$0.11\lambda_o$	$0.026\lambda_o$	$0.08\lambda_o$
Ws	*Ls*	*a*	*b*	Dt_1	Lt_1	*Wt*	Dt_2	Lt_2
9.0	8.2	10.1	8.0	1.6	7.0	0.4	8.3	6.0
$0.06\lambda_o$	$0.055\lambda_o$	$0.07\lambda_o$	$0.053\lambda_o$	$0.01\lambda_o$	$0.05\lambda_o$	$0.003\lambda_o$	$0.06\lambda_o$	$0.04\lambda_o$
$0.36\lambda_o$	$0.33\lambda_o$	$0.4\lambda_o$	$0.32\lambda_o$	$0.06\lambda_o$	$0.28\lambda_o$	$0.02\lambda_o$	$0.33\lambda_o$	$0.24\lambda_o$

*Dimensions in free space wavelength for 2 and 12 GHz.

and are identified in Table 1. But from Fig. 6 we can see that due to the introduction of the second pair of slits, there is a significant fluctuation in the lower band. This means that the second slit worsens the impedance matching and still the impedance matching is not improved for 2.4 GHz WLAN band. A smoothing performance of the impedance characteristic at the lower-frequency band is achieved by making rectangular cuts in the ground plane. It is due to the additional resonant modes with the good impedance matching generated by the rectangular cut.

In the parameter study (Fig. 7), the side "*b*" of the rectangular cut is varied from 4 to 8 mm keeping the side "*a*" at 10.1 mm. When it is 8 mm, the lower band fluctuation is removed improving the impedance matching for lower band. Finally, the proposed antenna yields a widebandwidth ranging from 2 to 12 GHz for VSWR less than 2, which covers the 2.4 GHz WLAN and UWB bands except for the notched band from 5.1 to 5.9 GHz.

B) Radiation patterns

The radiation characteristics of the proposed antenna are also investigated. Figures 8 and 9 illustrate the simulated and measured *E*-plane and *H*-plane radiation patterns at 2.2, 3, 7, and 10 GHz. The presented radiation patterns are almost stable proving that the presence of slits does not affect the behavior of the radiation pattern. *E*-plane is the *x–z* plane and *H*-plane is the *x–y* plane with reference to the antenna orientation defined in Fig. 2. In the *H*-plane, the pattern has omni-directional shape for the operating frequencies, whereas in the *E*-plane the pattern is bidirectional since there is a null in the feed line direction ($\theta = 90°$) that is parallel to the *z*-axis. It is also noted that *H*-plane pattern shows relatively large cross-polarization than *E*-plane pattern. This behavior is largely due to the strong horizontal components of the surface current at the frequencies out of the notch-band frequency because the vertical component of the surface current is the main contributor to the radiation and the horizontal component contributes to the cross polarization. It is obvious from these results that the radiation patterns are acceptable over the WLAN and UWB bandwidths. Also, it is observed that the radiation patterns at other frequencies out of the notched frequency band are about the same as those of the reference antenna (not shown).

C) Gain

Figure 10 shows the measured peak gain of the proposed antenna against frequency. Gain of the reference antenna is also included for comparison. For the reference antenna, the peak gain is relatively constant over the band from 2.8 to 11.8 GHz. But for the proposed 2.4 GHz WLAN and UWB antenna, a sharp gain decrease occurs in the vicinity of 5.5 GHz due to the frequency notched function and the peak gain is nearly constant outside the notched band from 2 to 12 GHz. Thus, the antenna exhibits a stable gain across the operation band. All of the above demonstrate the band-notched function of the proposed antenna.

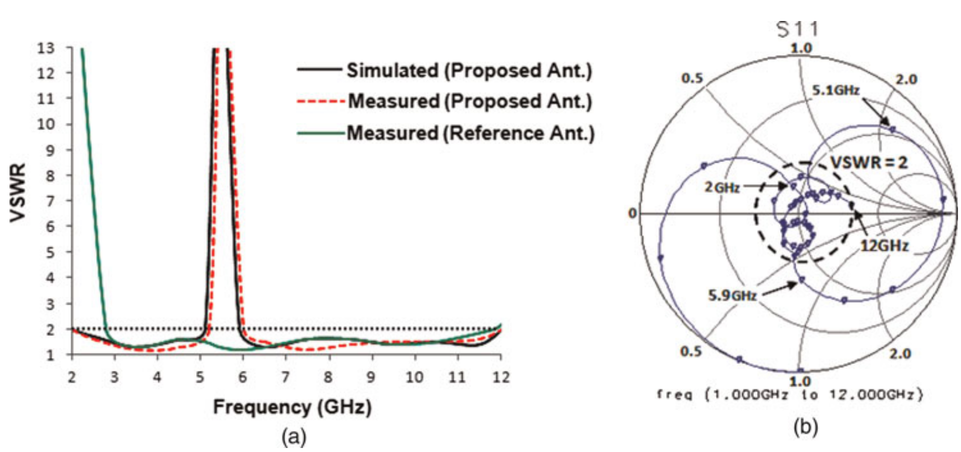

Fig. 4. (a) The measured and simulated VSWR of the reference and proposed antennas. (b) Simulated input impedance on Smith chart (proposed antenna).

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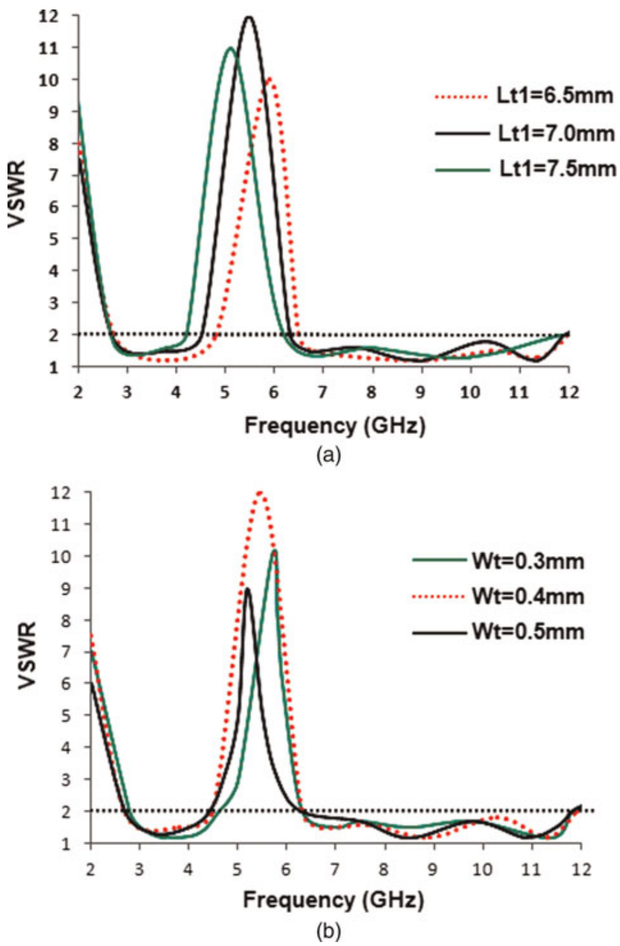

Fig. 5. Simulated VSWR results for the proposed antenna in terms of dimensions (a) L_{t1} and (b) W_t, respectively; the other parameter keeps the same as given in Table 1.

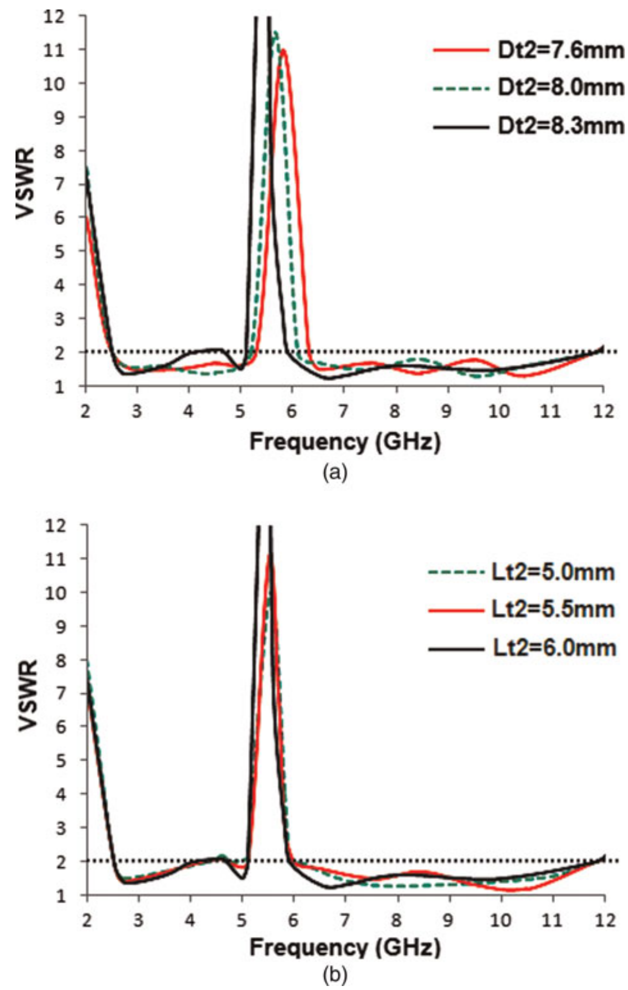

Fig. 6. Simulated VSWR results for the proposed antenna in terms of dimensions (a) D_{t2} and (b) L_{t2}, respectively; other parameters keep the same as given in Table 1.

IV TRANSFER FUNCTION AND TIME-DOMAIN STUDY

A) Transfer function

The UWB antenna can be viewed as a filter with some magnitude and phase responses. Since the UWB systems use short pulses to transmit signals, the transient properties of UWB antennas can be characterized by using the antenna transfer function in which the magnitude and the group delay are included. In general, the phase response and group delay are related to the antenna gain response. Moreover, the group delay is able to clearly show any nonlinearity that may be present in the phase response and it is required to be nearly constant. Otherwise, the phases are no longer linear in the far-field region and pulse distortion is caused. This can be a serious problem in a UWB communication system [25]. Hence, group delay is an important factor in UWB antenna system. In the performance evaluation of the proposed antenna, the antenna system is considered as a two-port network and the transmission scattering parameter S21, which indicates the transfer function, is measured. In this study, a pair of proposed antennas is used as the transmitting and receiving antennas. The antennas are connected to the ports of the network analyzer in the face-to-face scenario and the distance between them is kept at 20 cm. The longer distance indicates that the proposed antenna can work in a larger area. It should also be noted that the measurement was performed in a real environment with reflecting objects in the surrounding area. The measured amplitude of S21 is shown in Fig. 11(a). It is seen that the antenna has an attenuation of

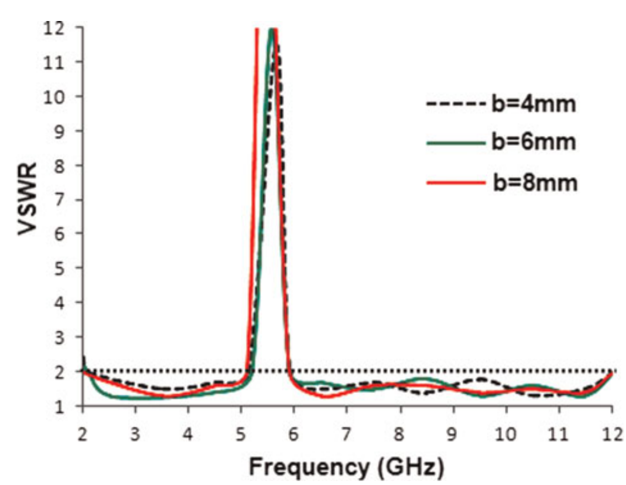

Fig. 7. Simulated VSWR result for the proposed antenna in terms of dimension "*b*"; other parameters keep the same as given in Table 1.

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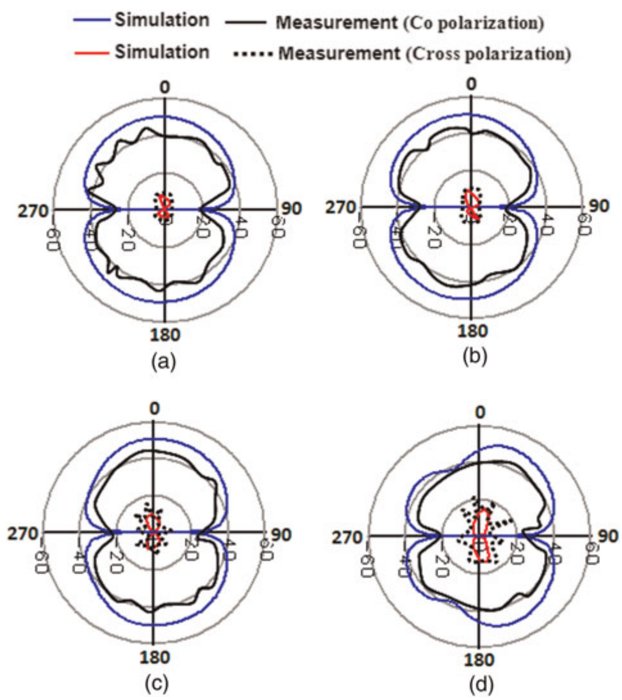

Fig. 8. Measured and simulated *E*-plane (*x*–*z* plane) radiation patterns of the proposed antenna at (a) 2.2 GHz, (b) 3 GHz, (c) 7 GHz, and (d) 10 GHz.

about 40 dB in the notched band and the amplitude of *S*21 outside the notched band from 2 to 12 GHz is relatively flat. Figure 11(b) displays the measured group delay of the proposed antenna system. The variation of the group delay is within 1.5 ns across the whole 2.4 GHz WLAN and UWB except for the notched band in which the maximum delay is more than 5 ns. From this, it is known that the group delay of the notched band antenna corresponds well to the magnitude of *S*21.

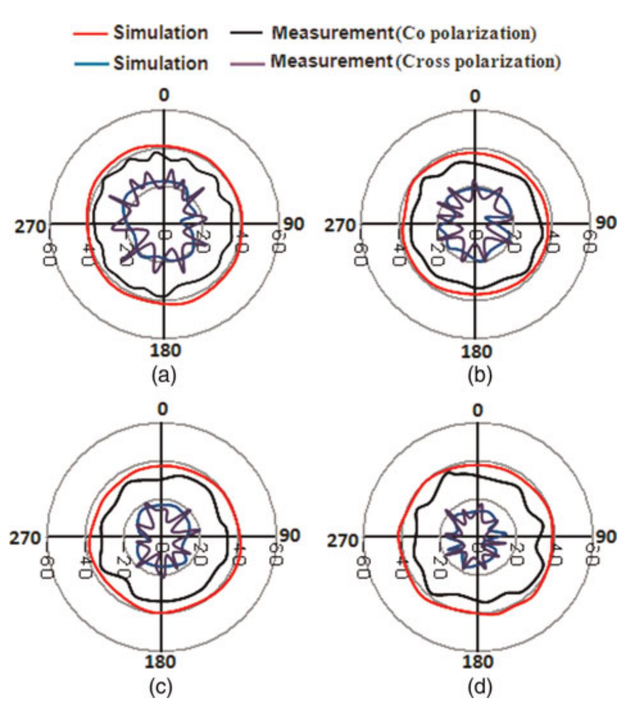

Fig. 9. Measured and simulated *H*-plane (*x*–*y* plane) radiation patterns of the proposed antenna at (a) 2.2 GHz, (b) 3 GHz, (c) 7 GHz, and (d) 10 GHz.

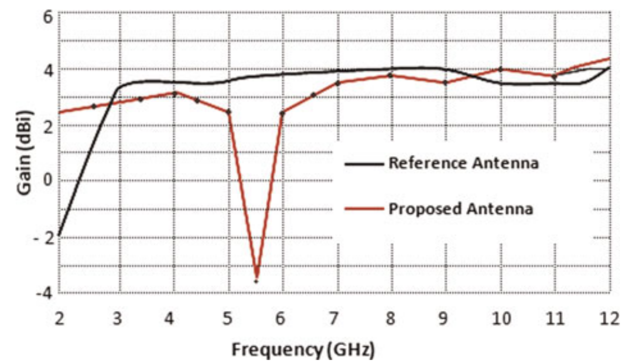

Fig. 10. Measured peak gain of the reference and proposed antennas.

B) Time-domain study

In this study, the antennas are set in head-to-head scenario as shown in Fig. 12. One of the antennas acts as a transmitter and the other one is a receiver. With this setup, the transmission characteristics in the "$+z$" direction can be evaluated. Figure 13 shows the excited pulse, radiated pulse, and received pulse of the notch-band antenna in the $+z$-direction. It shows that the radiated pulse and the received pulse are distorted as compared to the excited pulse. This is because of the transmission characteristics and the band-notched characteristics of the antenna. Now; we can study the fidelity to evaluate the characteristics of pulses.

The fidelity is defined as $\rho = \max_{\tau}\{|\int p(t)s(t-\tau)\,dt / \sqrt{\int p^2(t)\,dt}\sqrt{\int S^2(t)\,dt}|\}$.

This equation determines the correlation among the excited, the radiated, and received pulses. In general, excited

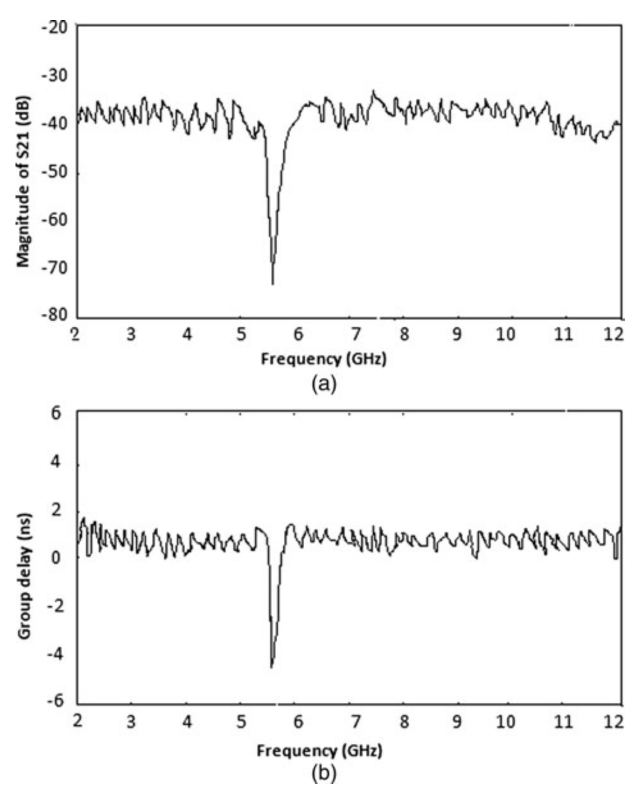

Fig. 11. The measured amplitude of *S*21 and group delay for the antenna system.

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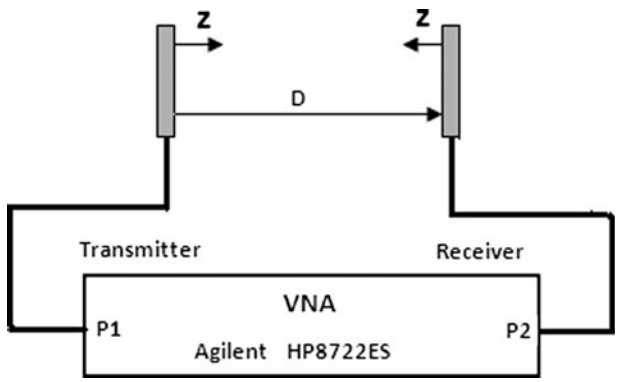

Fig. 12. The transfer function measurement setup.

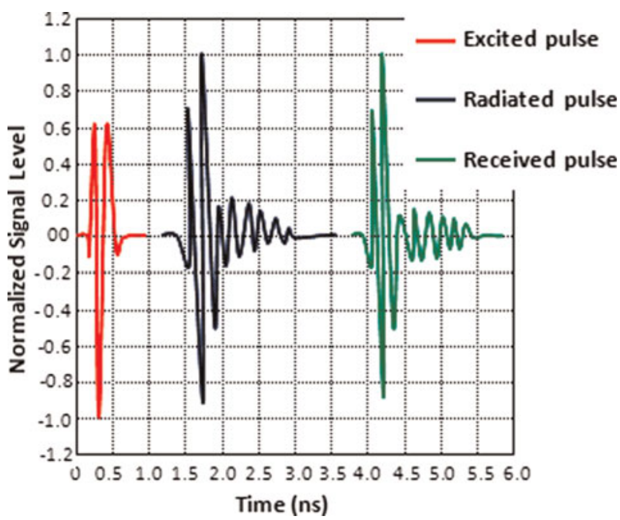

Fig. 13. The pulse waveforms for the antenna system.

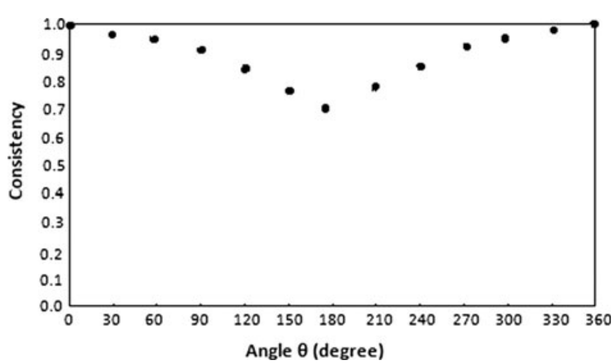

Fig. 14. Fidelity in the y–z plane.

pulses are chosen as the reference signals $p(t)$, while the radiated pulse and received pulse are taken as $s(t)$. In the above equation "τ" is a delay that is varied to make the numerator a maximum. In the fidelity study between the excited and radiated/received pulses in y–z plane, $p(t)$ is taken as the radiated pulse in the $+z$ direction and $s(t)$ as the radiated pulses at different directions in the y–z plane. Almost similar radiated waveforms are observed at $\theta = 0$, 30, and 60°. But, the radiated waveforms from $\theta = 90$ to 180° are distorted as compared to each other and have some ripples. Figure 14 shows the calculated fidelity in the y–z plane and it is seen that the consistency is more than 0.72.

V. CONCLUSION

A novel wideband CPW-fed slot antenna with 5 GHz band-notched characteristics for 2.4 GHz WLAN and UWB applications was presented and investigated. A prototype antenna has been designed, optimized, and measured for WLAN and UWB systems. The measured results well agree with the simulated results and the proposed antenna yields a wide bandwidth ranging from 2 to 12 GHz for VSWR less than 2 except for the notched band (5.1–5.9 GHz) for 5 GHz WLAN system. Moreover, it exhibits constant radiation pattern and has a favorable field gain and small group delay variations across the matching band except in the notched band, as a desirable feature for 2.4 GHz WLAN and UWB applications.

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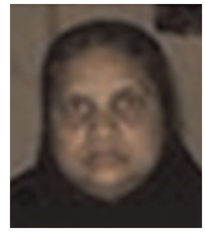

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