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Controllable triple band-notched monopole antenna for ultra-wideband applications

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Abstract: This study presents a new design of a triple band-notched ultra-wideband antenna. The designed structure of the antenna is based on two radiating strips, and a microstrip feed-line on the front, an inverted T-shaped element and a partial ground on the back. By etching a slot off the ground plane, another resonance is excited resulting in the extended bandwidth. The antenna with new structure occupies a small size of $20 \times 14\ \text{mm}^2$. The measured results show that the antenna has a wide bandwidth from 2.8 to 12.5 GHz for voltage standing wave ratio less than 2 apart from the rejected bands from 3.0 to 3.8 GHz, 5.1 to 6.1 GHz and 7.8 to 8.9 GHz. Meanwhile, radiation patterns and gain at various frequencies have been given.

1 Introduction

Ultra-wideband (UWB) communication system occupies the frequency band of 3.1 up to 10.6 GHz that has been approved by the Federal Communications Commission (FCC) [1]. The UWB antenna is one of the major subjects of UWB communication systems which has obtained a lot of attention because of its simple configuration, fast data transmission, small size and low cost. Having a broadband function on impedance bandwidth is one of the important properties of UWB communication systems. Thus, the big number of microstrip antennas with new designs and structures have been presented to meet this requirement [2–4]. The lower size and simplicity in design are two main advantages of the proposed antenna as compared with [2–4]. The proposed antenna against in [2–4] has seen a decrease about %77.5, %69.6 and %7.9, respectively. On the other hand, to enhance impedance bandwidth, a technique used in the proposed antenna (inverted U-shaped slot in the ground) is very simple. Out of benefits in UWB communication systems, however, there are the set of the interference frequency bands within UWB including the wireless local area network (WLAN) and Worldwide Interoperability for Microwave Access (WiMAX), which operate with the centre frequencies of 5.2 GHz (5150–5350 MHz), 5.8 GHz (5725–5825 MHz) for WLAN and 3.5 GHz (3400–3690 MHz), 5.5 GHz (5250–5850 MHz) bands for WiMAX and 8.025–8.4 GHz [International Telecommunications Union (ITU) 8 GHz]. To address this drawback, it is acceptable to be designed a special antenna with a tri-band-stopped characteristic to minimise potential interference. In the following years, multiband filtered UWB antennas based on different techniques have been suggested [5–9]. As compared with [5], the proposed antenna has smaller size than it in [5] (~57%). Another advantage is various techniques used in design. It means that in the proposed antenna, three techniques strip lines, defected ground structure (DGS), slot are used while in [5] just DGS is utilised. The proposed antenna is able to filter ITU band while in [5] it is not seen. If the proposed antenna be compared with [6], it should note that the size of the antenna nearly 55% has been decreased. In addition, the antenna is able to filter three notched bands against the dual notched band in [6]. In other references [7–9], there are disadvantages including two notched bands, bigger sizes and traditional techniques compared with the proposed antenna. All cases above show which the antenna could be a suitable candidate for UWB applications. Among these various technical methods, this paper suggests a new structure of antenna with two radiating strips, a microstrip feed-line extended, an inverted T-shaped element in the form of DGS and finally a partial ground. Furthermore, by etching an inverted U-shaped slot in the partial ground, the broad impedance bandwidth is achieved. The proposed triple band-notched antenna was successfully fabricated and measured, and the results show a reasonable agreement with the simulated ones. Section 2 describes the antenna design, discussions on results is presented in Section 3 followed by conclusive comments in Section 4.

2 Antenna design

The structure of the proposed antenna is exhibited in Fig. 1. The antenna is implemented on a cheap FR4 substrate with a compact size of $20 \times 14\ \text{mm}^2$, thickness 1 mm and relative permittivity $\varepsilon_r = 4.4$. The antenna includes two radiating strips, an extended microstrip feed-line, an inverted

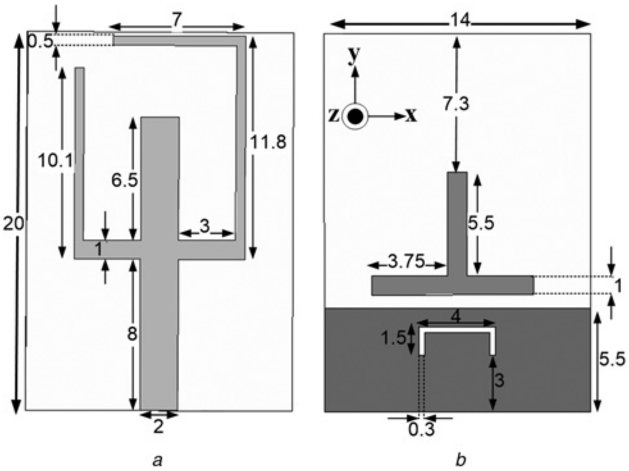

Fig. 1 *Geometry of the suggested antenna and its values*

a Front
b Back views (unit: mm)

T-shaped element in the form of DGS and a partial ground with an inverted U-shaped slot on it. As exhibited in Fig. 1, to achieve an acceptable impedance bandwidth, an inverted U-shaped slot is etched off the ground structure to generate another resonant frequency at nearly 12 GHz. Besides, in order to earn the stopped bands at centre frequencies of 3.5 and 5.5 GHz, respectively, the structure of radiating patch is changed to two radiating strips and an extended 50 Ω microstrip feed-line with width 2 mm. In addition, by using an inverted T-shaped coupling element in the form of DGS on the back, the third notched band is produced at 8 GHz. The antenna is optimised by both the electromagnetic (EM) simulation software of Ansoft High Frequency Simulation Structure (HFSS) based on the finite element method [10] and computer simulation technology (CST) with three-dimensional EM simulator [11]. In the next section, the antenna design procedure will be dealt, and the effect of various parameters on voltage standing wave ratio (VSWR) will be discussed.

3 Results and discussion

In the following stage, the triple notched band antenna with various parameters were fabricated, and the numerical and experimental results of the input impedance and radiation characteristics are shown. The parameters of the antenna are studied by varying one parameter at a time and fixing the others. Meanwhile, this part is divided into four sections of (a) full-band design, (b) notched band design, (c) time-domain analysis and (d) radiation characteristics.

3.1 Full-band design

In this portion, the design procedure of the UWB antenna with VSWR curves are demonstrated. Note that the simulated VSWR results are obtained using the HFSS [10]. As depicted in Fig. 2, VSWR for three antennas with various ground configurations are presented. VSWR curves for both of the Ant. 1 and Ant. 2 have two main resonant frequencies at approximately 4.5 and 9.5 GHz, respectively, which result in an impedance bandwidth from 3.7 to 10.3 GHz, whereas Ant. 3 with a U-shaped slot on the ground increases the bandwidth from 3.7 to 12.5 GHz by generating the third resonant frequency at 12 GHz.

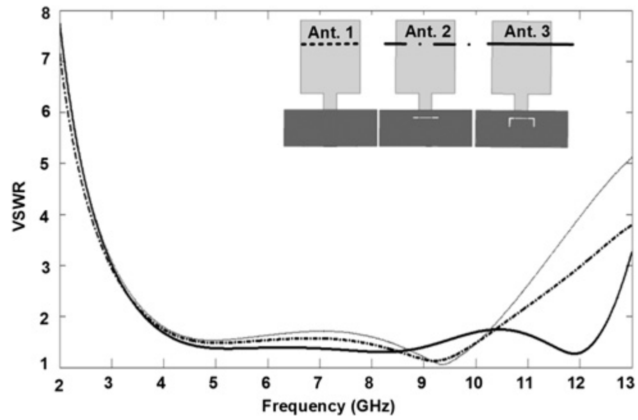

Fig. 2 *Comparison of simulated VSWR characteristics for the various ground structures*

As far as Fig. 3 is concerned, the antenna VSWR curves are exhibited for different values $dg1$. From Fig. 3 can be found out that the upper frequency of the impedance bandwidth is affected by using an inverted U-shaped slot in the ground plane, and also by optimising it, additional third resonant frequency is more excited. Furthermore, the upper-edge frequency of the impedance bandwidth is reduced from 12.5 GHz down to 9.2 GHz by increasing value $dg1$ from 1.5 to 2.0 mm. Therefore the optimised $dg1$ is 1.5 mm. Another point that we have a resonant frequency created at

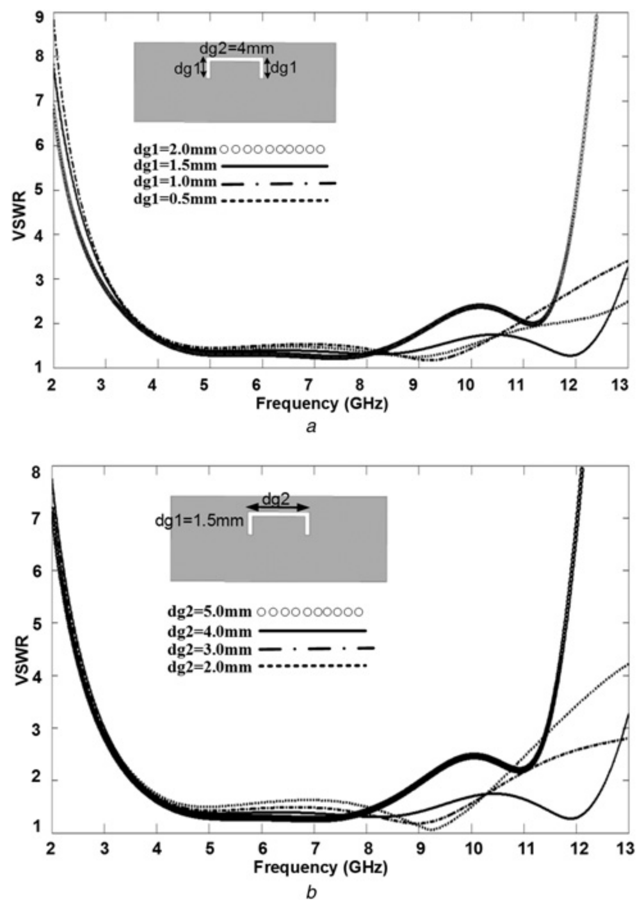

Fig. 3 *Simulated VSWR characteristics of the antenna with an inverted U-shaped slot on the ground for different values of*

*a dg*1
*b dg*2

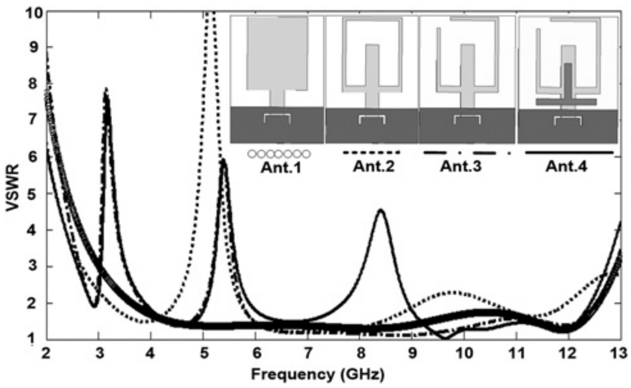

Fig. 4 *Comparison of simulated VSWR characteristics of the various antenna structures*

12 GHz. We know that the substrate used for the antenna is FR4 with characteristics $\varepsilon_r = 4.4$, $h = 1$ mm. Therefore effective dielectric constant at 12 GHz equals $\varepsilon_{\text{eff}} = 3.56$ and $\lambda_0 = 25$ mm, resulting in $\lambda_g = \lambda_0/\sqrt{\varepsilon_{\text{eff}}} = 13.2$ mm. With regard to Fig. 3, it is clear that length of U-shaped slot is 7 mm ($2 \times dg1 + dg2$). That it is approximately 0.52 λ_g.

3.2 Notched band design

In this section, the biggest aim is to filter three interference bands including WiMAX, WLAN and ITU bands, respectively. To reach to this aim, it has been tried to be used various techniques and new methods containing two radiating strips, extended microstrip feed line and finally DGS. By adjusting these three parameters, three notched bands at centre frequencies 3.5, 5.5 and 8 GHz can be obtained, respectively. To understand more, it is better to be paid attention to Fig. 4 which compares different VSWR curves for four various structures of the antenna. By looking at Fig. 4, the procedure for antenna design is distinguished. It is quite apparent from the figure that VSWR curve for Ant. 1 is quite flat without any notched band while by etching a U-shaped slot on the radiating patch, the first stopped band from 4.3 to 6 GHz is produced. This stopped band has two tangible disadvantages. The former it is very wide, the latter the impedance bandwidth of the upper band from 9 GHz onward is ruined. With comparison Ants. II and III, by varying ring radiating patch to two radiating stubs firstly the

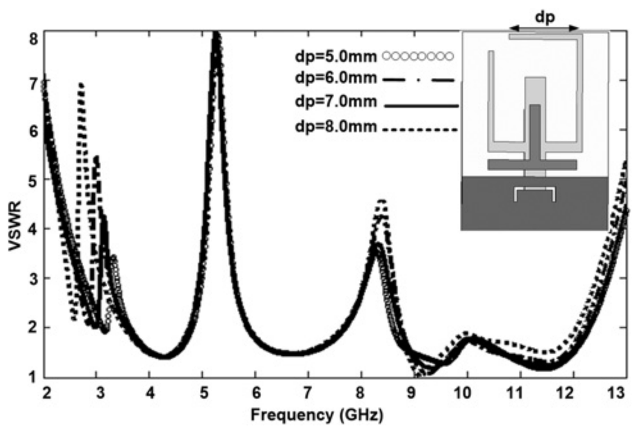

Fig. 5 *Simulated VSWR for different values dp*

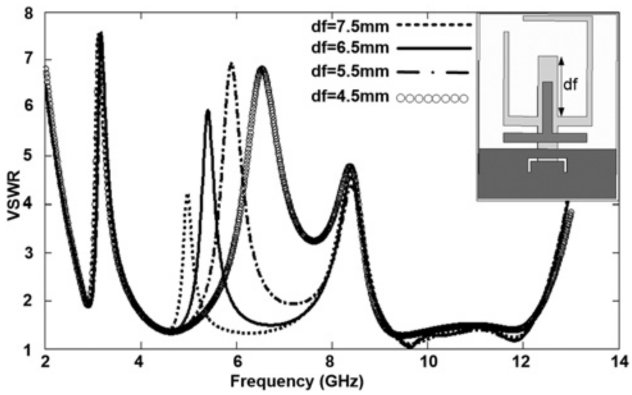

Fig. 6 *Simulated VSWR characteristics of the antenna for different values df*

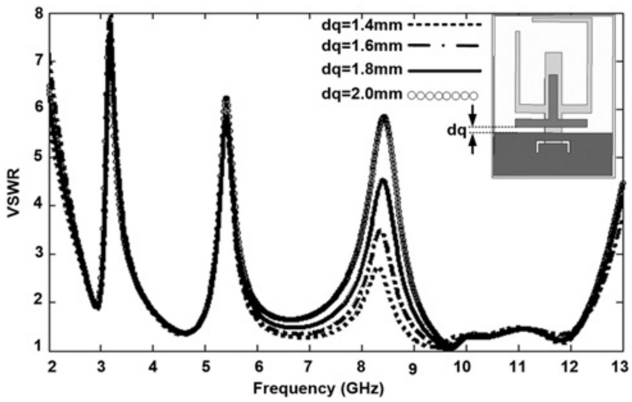

Fig. 7 *Simulated VSWR characteristics of the antenna for different values dq*

bandwidth is improved and secondly both notched bands at centre frequencies of 3.5 and 5.5 GHz are produced.

Simulated VSWR results of the antenna for different values *dp* is depicted in Fig. 5. As it is obvious, *dp* has a direct effect on the control of the central frequency of the lower notched band. In other words, the centre frequency is decreased from 3.5 to 2.8 GHz with an increasing *dp* from 5 to 8 mm. Since by shifting the lower notched band, both of the middle and upper notched bands are nearly station, thus it can be found out that the first notched band is controllable and independent. Regarding to favourable notched band (3.3–3.69), the best value of *dp* is 7.0 mm.

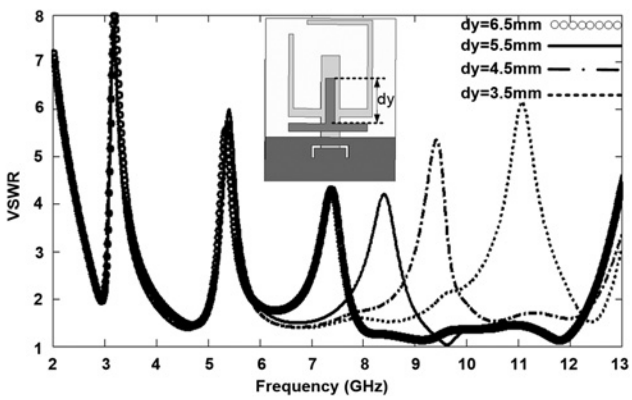

Fig. 8 *Simulated VSWR characteristics of the antenna for different values dy*

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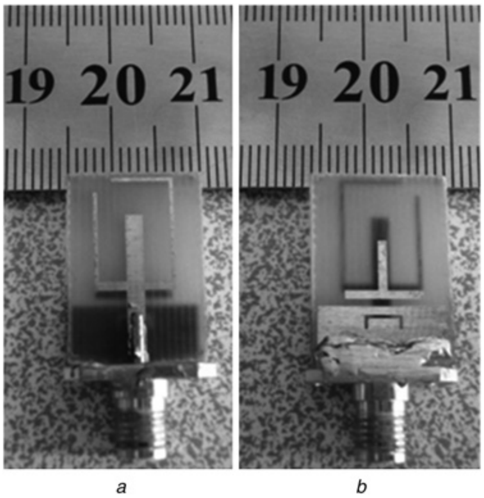

Fig. 9 *Photo of the fabricated antenna*

a Front view
b Back view

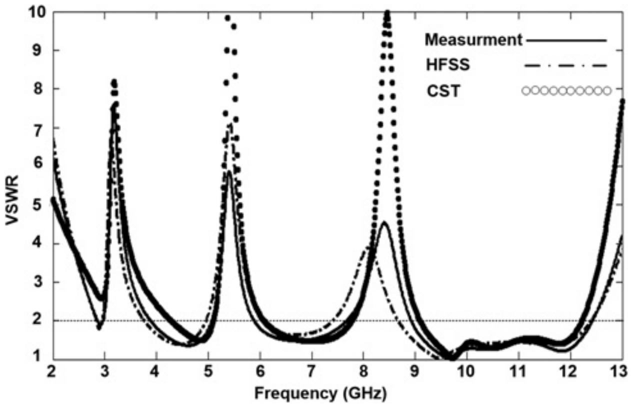

Fig. 10 *Measured and simulated VSWR of the antenna by both HFSS and CST*

As mentioned before, to achieve stopped band at centre frequency 5.5 GHz, the microstrip 50 Ω feed-line extended is used. Fig. 6 exhibits the simulated band-filtered feature by changing d*f*. As illustrated in Fig. 6, tuning the length of the feed-line can obtain a controllable centre-notched frequency range from 5 to 5.9 GHz for the second stopped band. Fig. 6 also shows that d*f* is a main

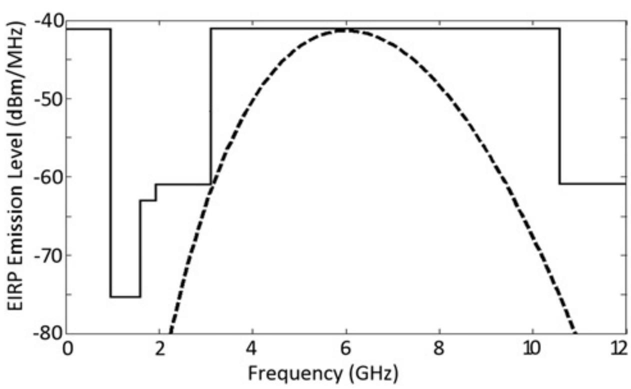

Fig. 11 *Power spectrum density compared to FCC mask*

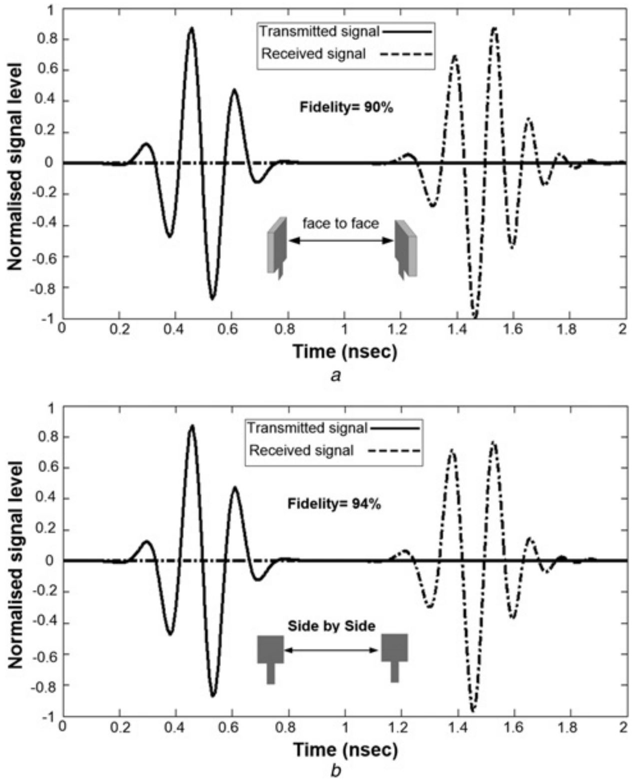

Fig. 12 *Transmitted and received pulses for a UWB link with antennas without notches in*

a Face-to-face
b Side-by-side orientations

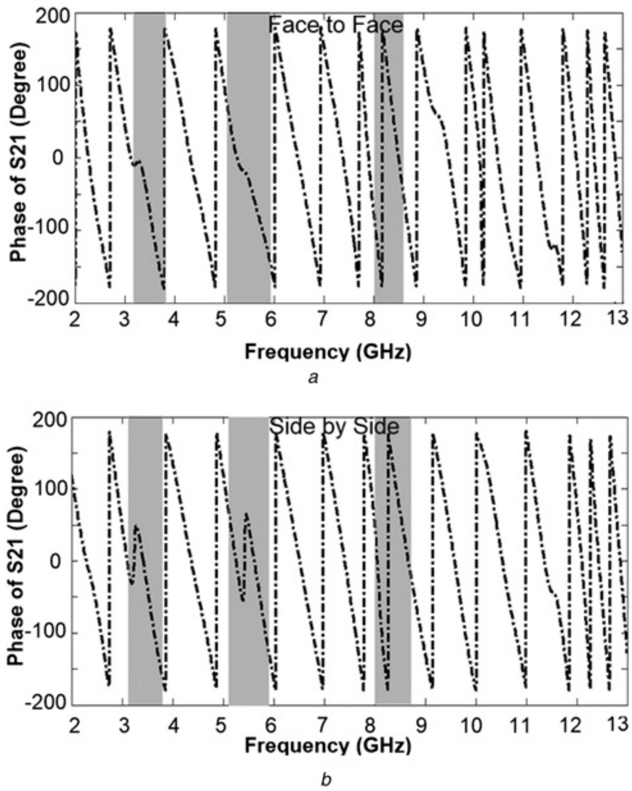

Fig. 13 *Simulated phase S21 with a pair of identical antennas in*

a Face-to-face
b Side-by-side orientations

factor to control the rejected VSWR value. As length d*f* increases from 4.5 to 7.5 mm, the central frequency of the notched band is reduced from 7 to 5 GHz. The acceptable value of d*f* is 6.5 mm. It is interesting to note that by frequency shifting the middle notched band, frequency position for both of the lower notched band and the upper notched band are constant indicating the middle notched band is also controllable and independent like the lower

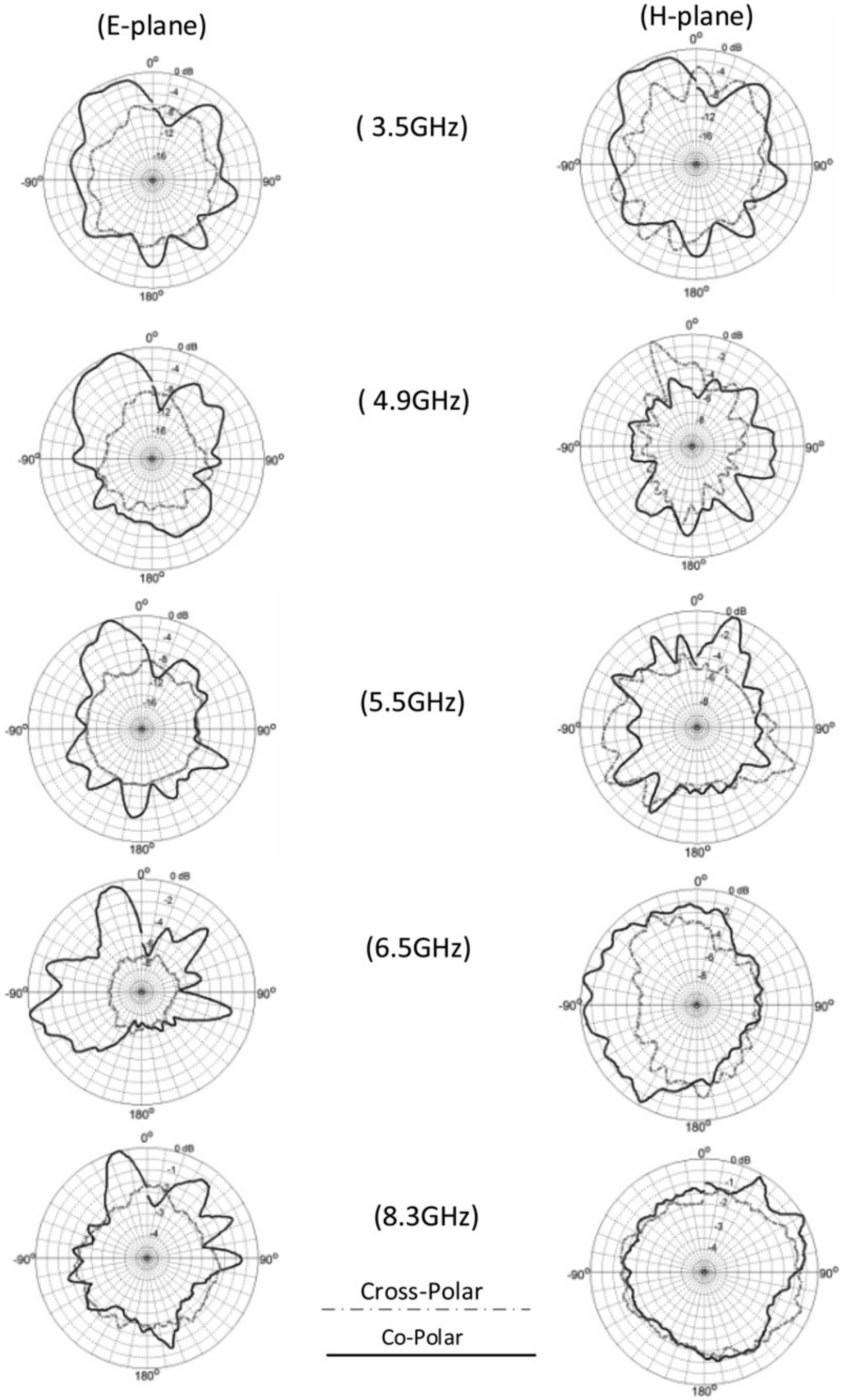

Fig. 14 *Measured normalised radiation patterns of the antenna at 3.5, 4.9, 5.5, 6.5 and 8.3 GHz*

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one. In order to earn the upper notched band, DGS technique is used containing an inverted T-shaped element on the back. As shown in Fig. 7, by varying parameter dq from 1.4 to 2.0, the VSWR value of the upper notched band at centre frequency about 8.5 GHz is increased from 2.5 up to 5.5 GHz. With regard to the frequency limitation of the upper notched band (8–8.4 GHz), the best value for parameter dq is 1.8 mm.

On the other hand, to achieve a frequency shift on the upper notched band, parameter dy can be the best parameter. As it is observable in Fig. 8, by varying parameter dy from 3.5 to 6.5 GHz, the centre frequency on the upper notched band is decreased from 11 GHz down to 7.5 GHz. To meet the frequency requirement related to FCC for ITU band, the suitable value for dy is 5.5 mm. A further point that, the upper notched band is controllable and independent right like both of the previous notched bands. The antenna was fabricated and tested in the Antenna Measurement Laboratory at Iran Telecommunication Research Center. The photos of the fabricated antenna in both front and back views are obvious in Fig. 9.

Fig. 10 exhibits the measurement and simulation results of VSWR for the antenna. In this figure, VSWR curves have been earned by both softwares HFSS [10] and CST [11]. The fabricated antenna is able to cover the frequency band from 2.8 GHz to 12.5 GHz for VSWR ≤ 2 except the notched bands from 3.0 to 3.8 GHz, 5.1 to 6.1 GHz and 7.8 to 8.9 GHz. In addition, this behaviour almost was predicted by HFSS and CST simulators. Good agreement between simulated and measured results is observed and a bit of difference between them is attributed to factors such as SMA connector effects, fabrication imperfections and inappropriate quality of the microwave substrate.

3.3 Time-domain analysis

One of interesting points about radiating of a pulse signal by antenna is related to computation of the dispersion in a way that the transmit transfer functions of the antennas are utilised to calculate the radiated pulse in various directions when a reference pulse is used at the antenna input. It is interesting to note that the signal must give an UWB spectrum covering the antenna impedance bandwidth (FCC mask) including 3.1 up to 10.6 GHz. It is depicted in Fig. 11 a desirable approximation to a FCC mask compliant pulse can be achieved with a Gaussian seventh derivative. The pulse is suggested in time domain by [12]

$$G(t) = A \cdot \exp(-t^2/2\delta^2) \tag{1}$$

$$G^n(t) = \frac{d^nG}{dt^n} = (-1)^n \frac{1}{(\sqrt{2}\delta)^2} \cdot H_n\left(\frac{t}{\sqrt{2}\delta}\right) \cdot G(t) \tag{2}$$

$$H_7(t) = 128t^7 - 1344t^5 + 3360t^3 - 1680t \tag{3}$$

The signal along with its spectrum are apparent in Fig. 11. The bandwidth related to the pulse is exactly into the mask. Furthermore, with a little negligibility, the sixth and eighth derivatives can be acceptable. A well-defined parameter named fidelity factor [13] is suggested to assess the quality of a received signal waveform according to the input signal,

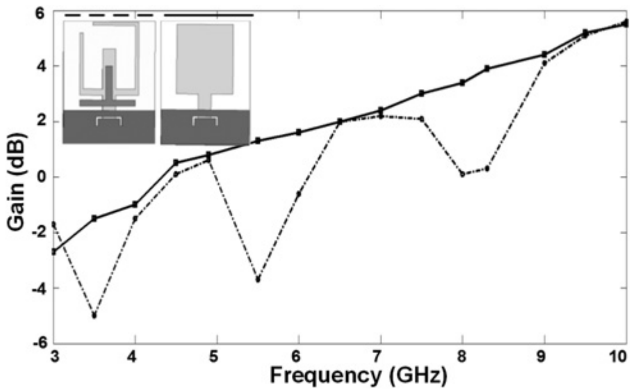

Fig. 15 *Gain comparisons for the ordinary square antenna (without notched band), and the proposed antenna (with notched band)*

as given in the following equation

$$F = \max_\tau \left| \frac{\int_{-\infty}^{+\infty} S(t) r(t-\tau) \mathrm{d}t}{\sqrt{\int_{-\infty}^{+\infty} S(t)^2 \cdot \int_{-\infty}^{+\infty} r(t)^2 \mathrm{d}t}} \right| \tag{4}$$

$S(t)$ and $r(t)$ are, respectively, TX and RX signals. Having a high degree of correlation between TX and RX signals in UWB systems is very necessary.

To evaluate the pulse transmission characteristics of the proposed antenna, two structures in side-by-side and face-to-face orientations were selected. The distance between the transmitting and receiving antennas is d = 25 cm [14]. As shown in Fig. 12, a relatively desirable similarity exists between the RX and TX pulses. By (4), fidelity factor in face-to-face and side-by-side configurations was obtained which they equal 0.90 and approximately 0.94, respectively. The values of fidelity factor indicate that the proposed antenna imposes negligible effects on the transmitted pulses. Phase S21 for side-by-side and face-to-face orientations are also shown in Fig. 13. As before predicted, the plot exhibits a linear variation of phase in the total operating band except notched bands. It is important to note once again which the distance between both the identical antennas in side-by-side and face-to-face orientations is 25 cm which has been extracted from [14].

3.4 Radiation characteristics

Fig. 14 depicts the measured normalised far field radiation patterns in both the H-plane (x–z plane) and the E-plane (y–z plane) at frequencies 3.5, 4.9, 5.5, 6.5 and 8.3 GHz. It can be observed that the pattern structures are irregular because the antenna size is small (20 × 14 mm^2).

Fig. 15 exhibits the antenna gains without and with notched bands. As illustrated in Fig. 15, three sharp decrease of maximum gain on stop bands at 3.5, 5.5 and 8.3 GHz are apparent. For other frequencies outside notched bands, the antenna nearly has a flat gain.

4 Conclusions

In this paper, a new controllable triple band-notched UWB monopole antenna was presented. The fabricated antenna can cover a broad impedance bandwidth from 2.8 to 12.5 GHz with three notched bands about 3.0–3.8 GHz, 5.1–6.1 GHz and 7.8–8.9 GHz from interference bands of WiMAX, WLAN and ITU bands, respectively. The proposed antenna has a small configuration with a compact size $20 \times 14 \times 1$ mm^3 and a simple geometry. Measurement results depict that the antenna could be a desirable candidate for UWB communication systems.

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