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A Penta Band Notched Elliptical Planar Monopole Antenna for UWB Applications

Devireddy S. Rao* and Immadi Govardhani

Abstract—In this work, an elliptical planar monopole Penta band-notched ultra-wideband (UWB) antenna is proposed. Band rejection at 2.4–2.6 GHz IEEE 802.11 b/g/n, 3.3–3.75 Wi-MAX, 3.9–4.2 GHz C-band satellite communication, 5.15–5.85 WLAN, and 7.9–8.4 GHz X-band satellite communication frequencies is achieved by etching slots in the radiating patch, feed line, and ground plane. The effect of the slot length on the notched band is also studied. The proposed antenna has been fabricated and tested. The measured impedance bandwidth of the antenna is 2.15–12.5 GHz, which covers bands of Bluetooth and UWB applications. The peak gain of the proposed antenna is 8 dB and drops drastically at notched bands. The proposed antenna shows good omnidirectional radiation patterns in the passbands.

1. INTRODUCTION

Ultra-wideband (UWB) communication systems have gained more attention since 2002 because of its wideband (3.1–10.6 GHz), low profile, high signal quality, and low power consumption. However, one of the major design issues in this UWB communication systems is interference from existing high power narrowband communication systems, such as wireless local area networks operating in 2.45 GHz (2.4–2.484 GHz), 5.25 GHz (5.15–5.35 GHz), 5.75 GHz (5.725–5.825 GHz) bands, Wi-MAX operating in 3.3–3.7 GHz band, C-band satellite communication downlink band (3.9–4.2 GHz), uplink band (5.9-6.2 GHz), and X-band satellite communication uplink (7.92–8.395 GHz), downlink (7.252–7.75 GHz) [1–5]. The method of adding an external band rejection filter to an antenna for mitigating the interference leads to rise in size and complexity of the system [15]. A UWB antenna with band-notched properties is a better solution to avoid these electromagnetic interferences, without affecting the size and complexity of the system. Recently, a good number of techniques have been proposed in literature to achieve band notch characteristics such as adding parasitic strips to the patch [4], Complementary Split-Ring Resonator (CSRR) [5, 21], Split-Ring Resonators (SRR) [6, 22], $\lambda/4$ length stubs [7], meander line structures [8], and slots [9, 16]. Among these techniques, the most prevailing and simple technique is integrating a narrow slot into the radiator. These slotted antennas can provide low dispersion and high radiation efficiency.

In the literature, a round-shaped radiating patch loaded with a folded slot and C-shaped strips is placed on both sides of the feed line to achieve Wi-MAX and WLAN band-notched characteristics [10]. A hexagon-shaped patch fed by stripline is proposed in [11]. In this work, triple band notch characteristics at 3.3–3.7 GHz, 5.3–5.7 GHz, and 7.2–7.7 GHz are generated with complementary split-ring resonators (CSSR) and two inverted T-shaped conductors inserted in the antenna backside. A rectangle-shaped patch with a defected ground structure is proposed in [12]. This coplanar waveguide (CPW) feed antenna covers the bandwidth of 2.5–11.5 GHz. Two identical L-shaped $\lambda/4$ stubs are attached to the

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* Corresponding author: Devireddy S. Rao (sreenu.98@gmail.com).
The authors are with the Department of ECE, Koneru Lakshmaiah Education Foundation, Vaddeswaram, Guntur, Andhra Pradesh, 522502, India.

ground plane to achieve the band notched performance from 5.2 to 5.75 GHz (WLAN band). A parasitic element is formed in the radiating element to gain a notch band from 3.3 to 3.6 GHz (Wi-MAX band). A UWB monopole antenna with four notched bands at WLAN (2.44–2.77 and 5.45–5.98), Wi-MAX (3.42–9.97 GHz), and ITU (8–8.68 GHz) is presented in [13]. These band-notched characteristics are achieved by integrating three C-shaped slots in the radiating patch and another one in the feed line.

However, in the literature most of the band-notched antenna models have single, dual, triple bands, and very few have quadruple notched bands. To minimize the interference to a negligible level, it is necessary to reject a greater number of bands. So, in this paper, we present an antenna that can reject five narrow bands by creating narrow slots on the radiating patch and ground plane. The effect of the slot length on notch band frequency is studied using High-Frequency Structural Simulator (HFSS) tool. Good agreement is observed between simulated and measured results. The following sections discuss the proposed antenna structure, evaluation, its working, results, and discussions.

2. ANTENNA DESIGN

The aim of the proposed research is to design a UWB antenna with Penta band-notched characteristics. The geometry of the proposed elliptical Penta band-notched UWB antenna design and a photograph of the fabricated antenna are shown in Figure 1. The antenna is constructed on an economical FR4 substrate with a thickness of 1.6 mm, relative permittivity of 4.4, and loss tangent of 0.019. The comprehensive size of an antenna is $34 \times 46 \times 1.6\,\text{mm}^3$. The design process of the proposed antenna is depicted in Figure 2.

The proposed antenna comprises an elliptical radiating patch which is fed by 50-ohm microstrip line along the major axis as shown in Figure 2. The ratio between the major axis and the minor axis

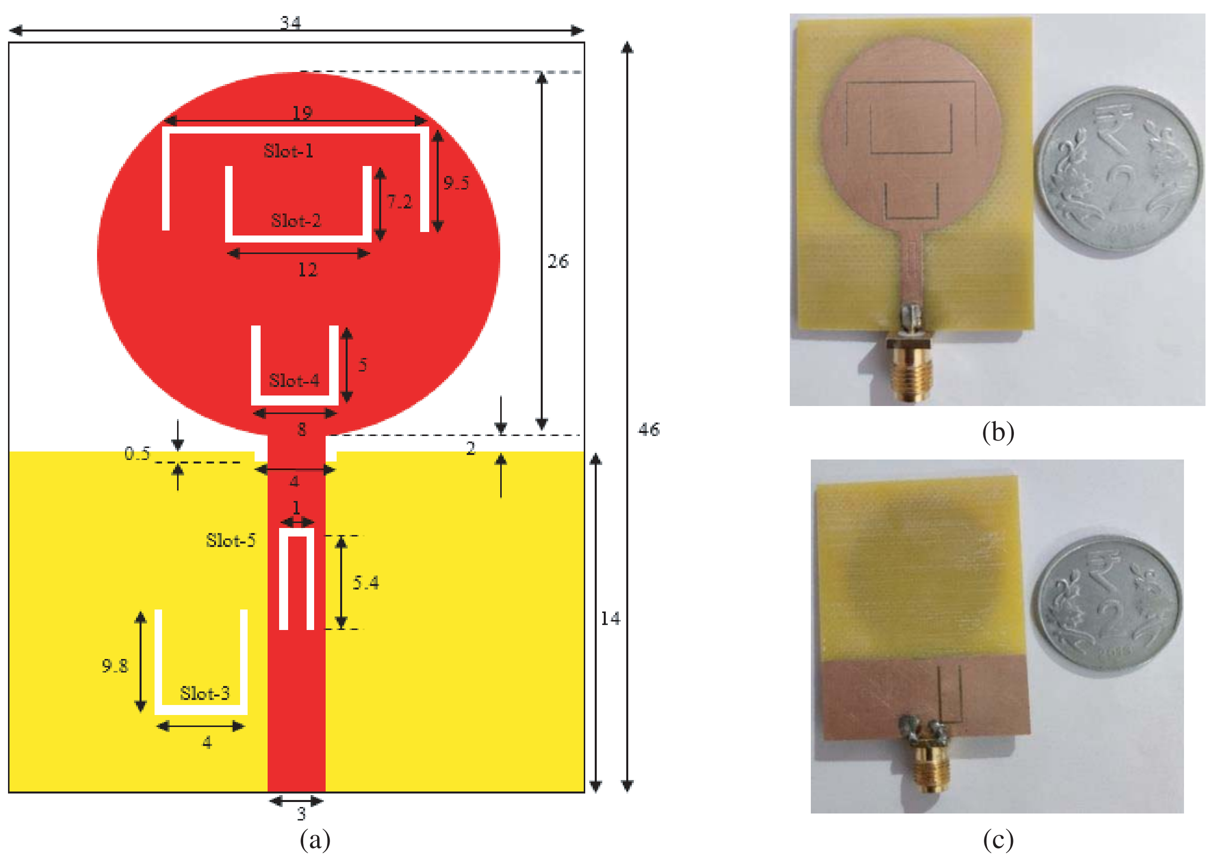
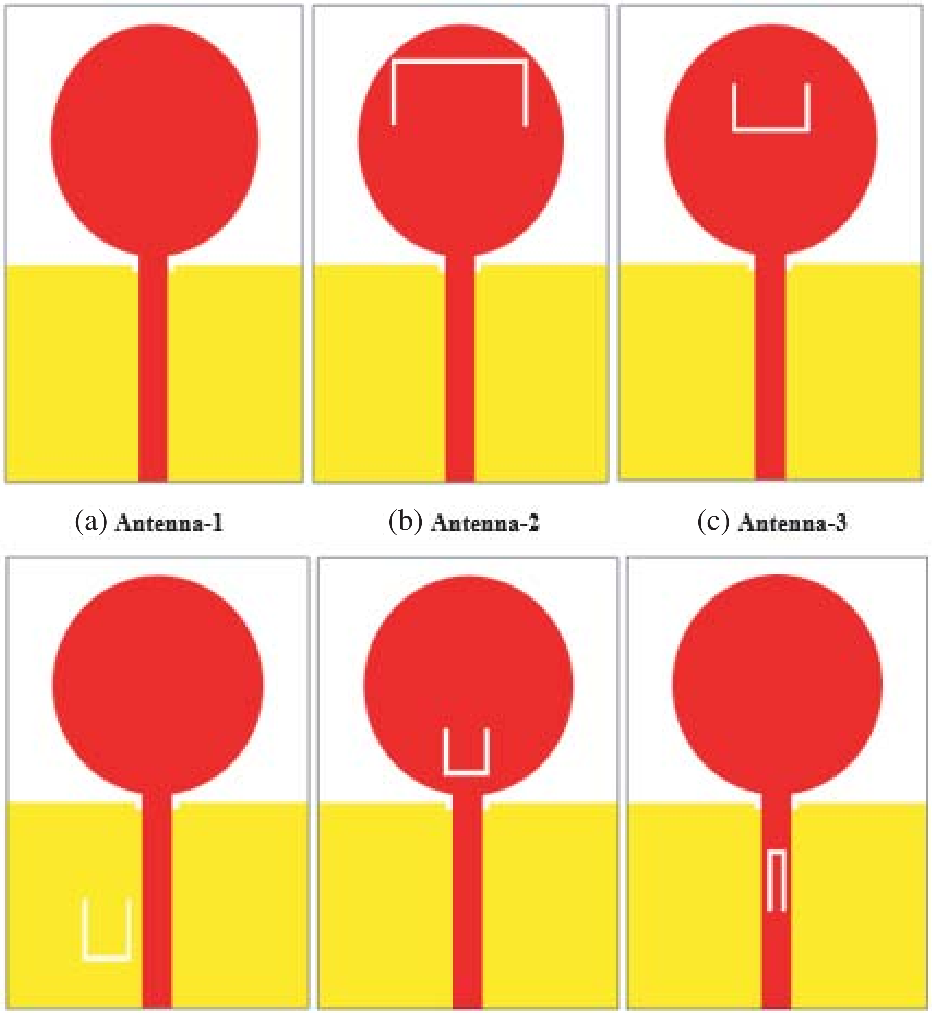


Figure 1. (a) Layout of the proposed antenna (b) Fabricated antenna front view and (c) Fabricated antenna bottom view. All dimensions are in mm.



(a) Antenna-1 (b) Antenna-2 (c) Antenna-3

(d) Antenna-4 (e) Antenna-5 (f) Antenna-6

Figure 2. Various designs of the proposed UWB antenna: (a) Without notch band. (b) With band notch at ISM. (c) With band notch at Wi-MAX. (d) With band notch at C-band. (e) With band notch at WLAN. (f) With band notch at X-band.

is taken as 1.1 to get the broadband characteristics. The lowest frequency of the broadband antenna is f_L which is given in Equation (1) as follows [2],

$$f_L(\text{GHz}) = \frac{c}{\lambda} = \frac{7.2}{L + r + p} \tag{1}$$

The length (L) and radius (r) of the cylindrical monopole antenna are resolved by equating its area as:

$$2\pi r L = \pi ab \tag{2}$$

$$\text{Let, } L = 2b \tag{3}$$

$$\text{then } r = \frac{a}{4} \tag{4}$$

where 'p' is the gap between the ground plane and radiating patch. From Equation (1), the major axis (b) and minor axis (a) of the radiating patch are 1.302 cm and 1.183 cm, respectively. The gap p between patch and ground plane is 0.2 cm to get the lowest frequency 2.3 GHz.

2.1. Effect of Slots on the S-Parameters

The band notch function is obtained when the length of the band notch resonator is of half-wavelength or quarter-wavelength at the notch-band center frequency. In this work, slots are used as band notch resonators. Three slots on the radiating patch, one slot on the feed line and another one in the ground plane, are created to obtain band notch characteristics. The length denoted by L_{ni} of each slot is calculated by using Equation (5):

$$L_n = \frac{c}{2f_n\sqrt{\varepsilon_{\mathit{eff}}}} = \frac{\lambda}{2} \tag{5}$$

where L_n denotes the length of the slot, $\varepsilon_{\mathit{eff}}$ the effective dielectric constant ($\varepsilon_{\mathit{eff}} = \frac{\varepsilon_r+1}{2}$), ε_r the dielectric constant, and c the light velocity.

The proposed antenna is fabricated on an FR4 substrate, which has a dielectric constant of 4.4, so the effective a dielectric constant is 2.7. The theoretical length of all slots is calculated using Equation (5), and simulated (practical) lengths are through Equations (6) to (10) and tabulated in Table 1. It is observed from Table 1 that the deviation is negligible between practical and theoretical lengths.

$$L_{n1}(\text{at } 2.4\,\text{GHz}) = 2(9.5) + 19 \tag{6}$$
$$L_{n2}(\text{at } 3.45\,\text{GHz}) = 2(7.2) + 12 \tag{7}$$
$$L_{n3}(\text{at } 3.9\,\text{GHz}) = 2(9.8) + 4 \tag{8}$$
$$L_{n4}(\text{at } 5.0\,\text{GHz}) = 2(5.0) + 8 \tag{9}$$
$$L_{n5}(\text{at } 7.7\,\text{GHz}) = 2(5.4) + 1 \tag{10}$$

where λ is the wavelength, and L_{n1} to L_{n5} are the lengths of slot-1 to slot-5, respectively.

Table 1. Theoretical and practical lengths of the slots at various notch frequencies.

Band notch frequency (GHz)	Theoretical length L_n in mm	Practical length L_n in mm	Practical Width in mm
2.4	38.03	38.00	0.3
3.45	26.46	26.40	0.3
3.9	23.40	23.60	0.5
5.0	18.20	18.00	0.5
7.7	11.85	11.80	0.3

Slot-1 is created on the patch of antenna-1 which forms antenna-2 to reject interference from the IEEE 802.11 b/g/n (2.4 GHz) band. Similarly, inserting slot-2 on the patch avoidd the Wi-MAX band (3.3–3.7 GHz) interference. To mitigate the frequency interference from the C-band satellite communication downlink band (3.9–4.2 GHz), slot-3 is inserted in the ground plane. Slot-4 is embedded on the patch to minimize the interference of the WLAN band (5.15–5.35 GHz and 5.725–5.825 GHz). Finally, slot-5 on the feed line is responsible for eliminating interference from the X-band satellite communication uplink frequency band (7.9–8.4 GHz). Figure 3 shows the simulated S_{11} plots which illustrate the band notch functions for the different antenna models.

The crucial parameters of a band-notched antenna are the center frequency and bandwidth of the notch band. The effects of various lengths and widths of an inverted U-shaped slot (i.e., slot-1) on the band-notched characteristics of proposed the antenna are discussed in Figure 4. It is observed that the center frequency of the notch band is shifted from 2.64 to 2.33 GHz as the length of slot-1 is changed from 36 to 40 mm. Also, by changing the width of slot-1 from 0.2 to 1 mm, the bandwidth of the notch band is increased from 200 to 500 MHz. The desired band-notch at 2.4–2.6 GHz obtained for slot-1 length of 38 mm and width of 0.3 mm and hence is used in the proposed antenna.

Similarly, a U-shaped slot (slot-2) is embedded on the patch to achieve band rejection at 3.3–3.5 GHz as shown in Figure 2(c). Slot-2 length is estimated by Equation (7). The parametric analysis

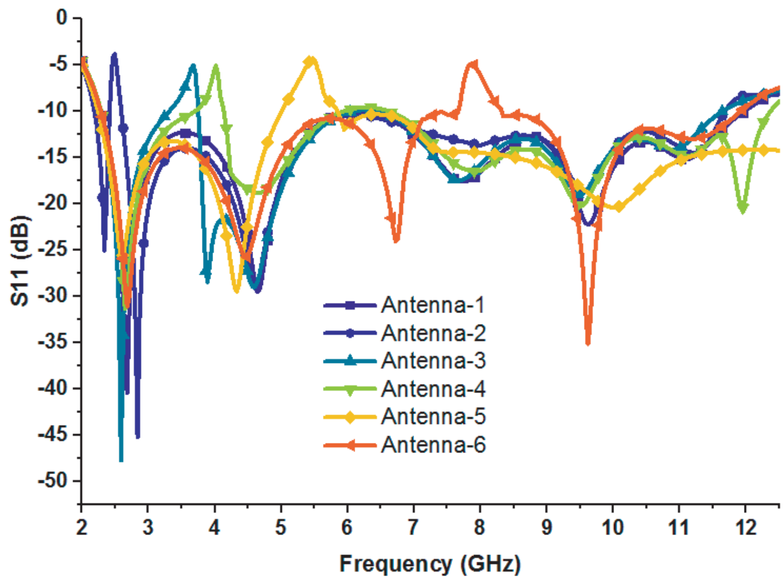


Figure 3. Simulation results of S_{11} for different antenna models of proposed design.

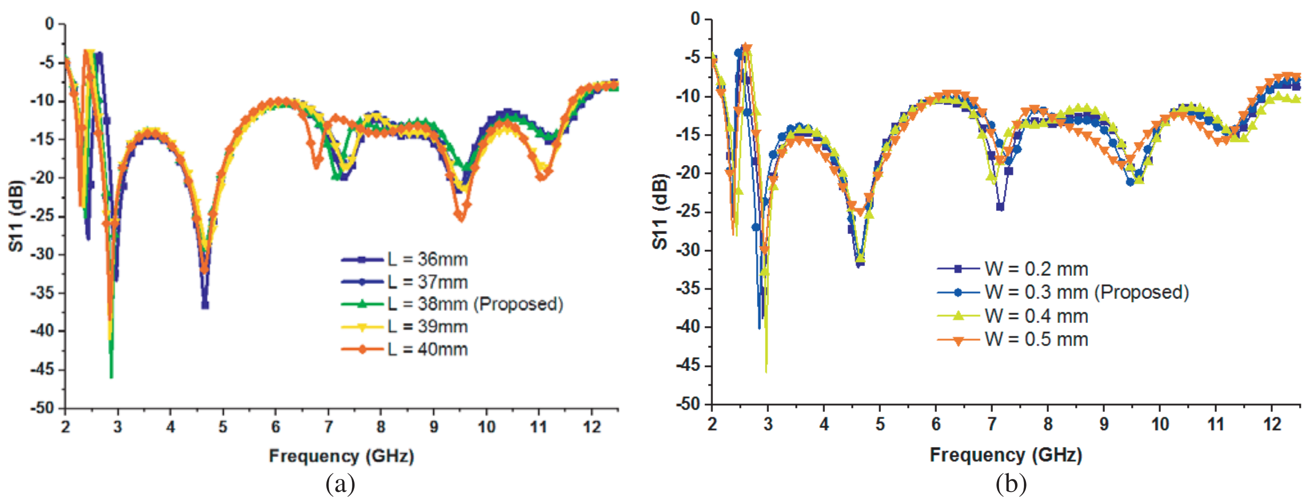


Figure 4. Simulated S_{11} plot for (a) different lengths of slot-1 (b) different widths of slot-1.

is done at different lengths and widths to understand the impact on band notch characteristics which are depicted in Figure 5. It is observed that the center frequency of the notch is shifted to left from 3.9 to 3.4 GHz as the length of slot-2 is varied from 24.4 to 28.4 mm. Also, by changing the width of slot-2 from 0.3 to 1 mm, the bandwidth of the notch band is increased from 400 to 700 MHz. The desired band rejection at 3.3–3.7 GHz is gained for a slot length of 26.4 mm and a width of 0.3 mm.

Another U-shaped slot is integrated with ground denoted as slot-3 as shown in Figure 2(d) is responsible for the notch at 3.9–4.15 GHz C-band. The total length of slot-3 at 3.9 GHz notch frequency is calculated using Equation (8) and is approximately equal to the half wavelength. The simulated length (23.6 mm) is almost equal to the theoretical length (23.4 mm). Figure 6 shows the simulated S_{11} at different lengths and widths of slot-3. S_{11} is -5.2 dB at the center frequency of the notched band (3.9 GHz). After parametric analysis on slot-3, it is understood that with respect to slot-3 length (21.6–24.6 mm), the center frequency of the notch band shifts towards left (4.45 GHz to 3.9 GHz). By varying the width of the slot-3 0.3 mm to 1 mm, the bandwidth of the notch is raised to 450 MHz from 220 MHz. The desired band rejection at 3.7–4.15 GHz is gained for a slot length of 23.6 mm and width

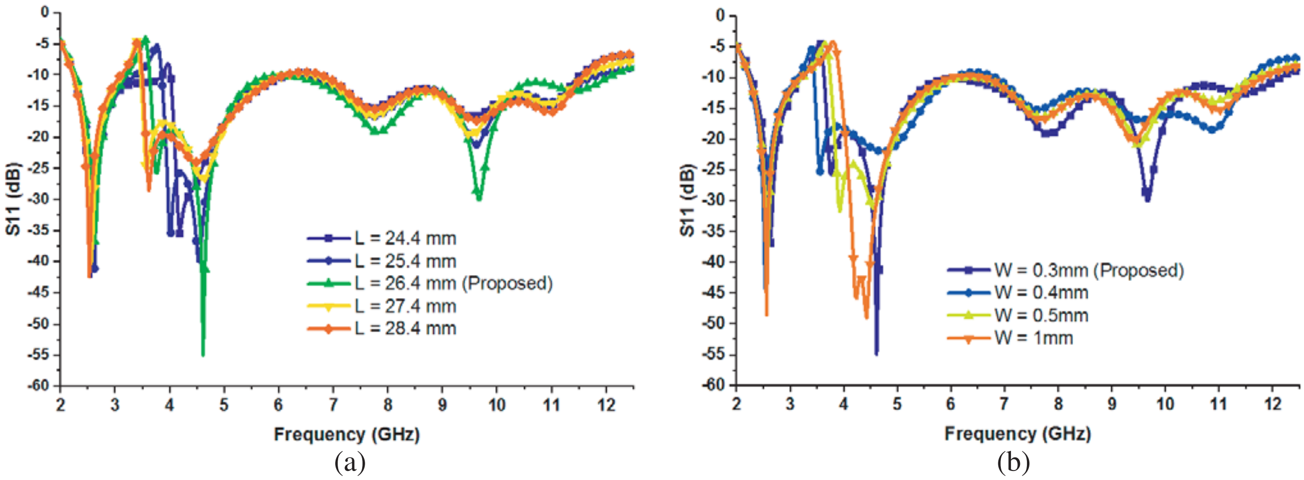


Figure 5. Simulated S_{11} plot for (a) different lengths of slot-2 (b) different widths of slot-2.

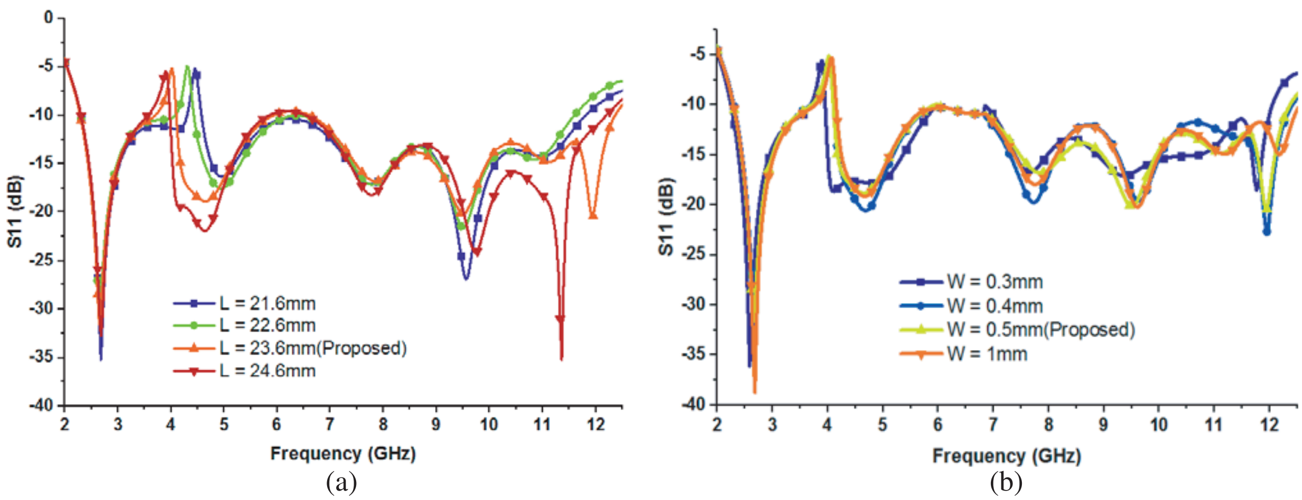
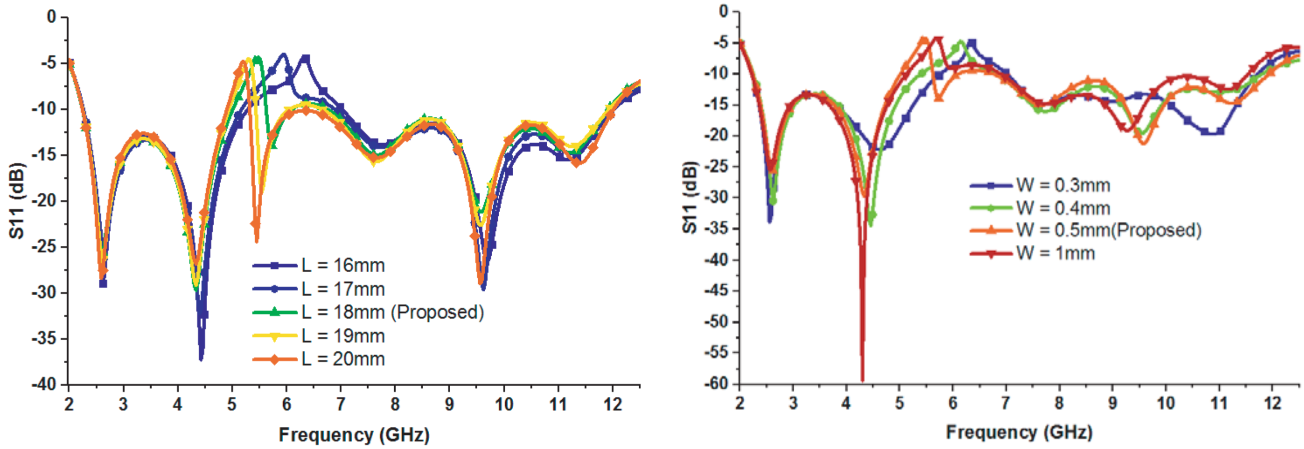


Figure 6. Simulated S_{11} plot for (a) different lengths of slot-3 (b) different widths of slot-3.

of 0.5 mm.

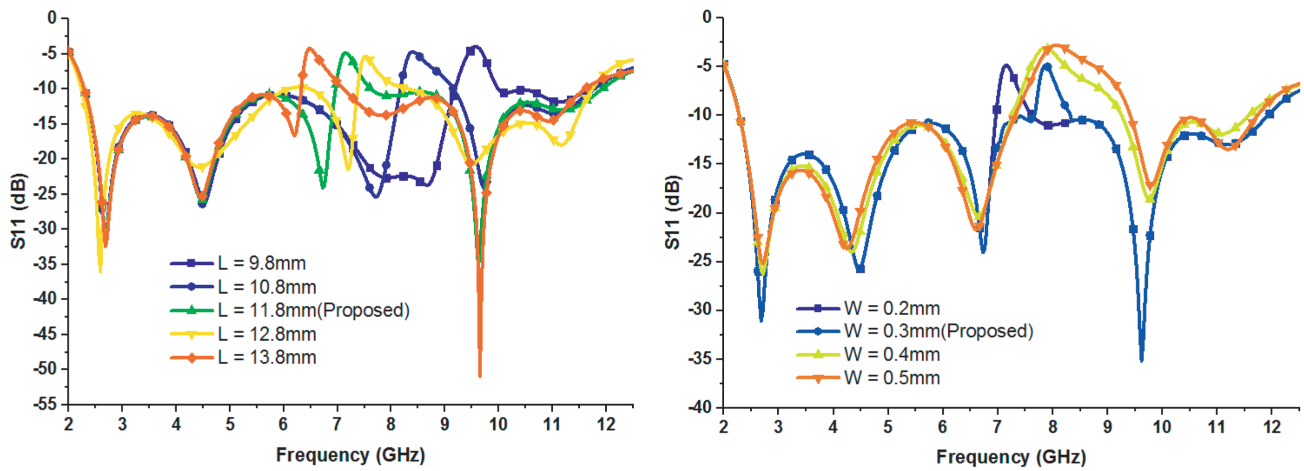
To create notch function at 5.1–5.7 GHz band, a U-shaped slot denoted as slot-4 is integrated with radiating patch and yields Antenna-5 as presented in Figure 2(e). This is accountable for the notch at 5.1–5.7 GHz WLAN band. The total length of slot-4 at 5 GHz notch frequency is calculated using Equation (9) and is approximately half wavelength. The simulated length (18 mm) is equal to the theoretical length (18.2 mm). Figure 7 shows simulated S_{11} at various lengths and widths. S_{11} is -4.2 dB at a center frequency of the notched band (5.5 GHz). It is understood that the center frequency of the notch band is moved from 6.3 to 5.15 GHz as the length of slot-4 is changed from 16 to 20 mm. Also, by changing the width of slot-4 from 0.3 to 1 mm, the bandwidth of the notch band is increased from 700 to 1500 MHz. The required band notch at 5.15–5.85 GHz is obtained for slot-4 length of 18 mm and width of 0.5 mm and hence is used in the proposed antenna.

Likewise, for the notch at 7.9–8.4 GHz X-band satellite communication band, an inverted U-shaped slot is formed on the feed line denoted as slot-5 to create Antenna-6 as exhibited in Figure 2(f). The total length of slot-5 at 7.7 GHz notch frequency is computed by using Equation (10) and is almost half wavelength. The simulated length is 11.8 mm, and the theoretical length is 11.85 mm. Figure 8 displays the simulated S_{11} at different lengths and widths. The simulated S_{11} is -4.8 dB at notched band center frequency. It is noted that the center frequency of the notch band is shifted from 9.5 to 6.45 GHz as the



(a) (b)

Figure 7. Simulated S_{11} plot for (a) different lengths of slot-4 (b) different widths of slot-4.



(a) (b)

Figure 8. Simulated S_{11} plot for (a) different lengths of slot-5 (b) different widths of slot-5.

length of slot-5 is changed from 9.8 mm to 13.8 mm. Also, by changing the width of slot-5 from 0.3 to 1 mm, the bandwidth of the notch band is increased from 600 to 1400 MHz. The desired band notch at 7.4–8.35 GHz is obtained for the slot-5 length of 11.8 mm and width of 0.3 mm and hence is used in the proposed antenna.

The simulated current distribution at the notched bands is depicted in Figure 9. It is seen that along the edges of the slot or around the slots, the current directions are in the opposite phases, and they cancel each other. So, these currents do not contribute to the radiation.

3. RESULTS AND DISCUSSION

In this section, the experimental results of the elliptical planar monopole UWB antenna with Penta band-notched characteristics are presented. Figure 10 illustrates the measured and simulated S_{11} as the function of frequency. There is a good agreement between measured and simulated results. The impedance bandwidth of the proposed antenna is 141% (2.15–12.5 GHz) with five notch bands at 2.4–2.6 GHz, 3.3–3.75 GHz, 3.9–4.2 GHz, 5.15–5.87 GHz, and 7.75–8.5 GHz. So, the proposed antenna has the capability to mitigate the interference from IEEE 802.11 b/g/n, Wi-MAX, C-band satellite communication downlink, WLAN, and X-band satellite communication uplink systems. At notch

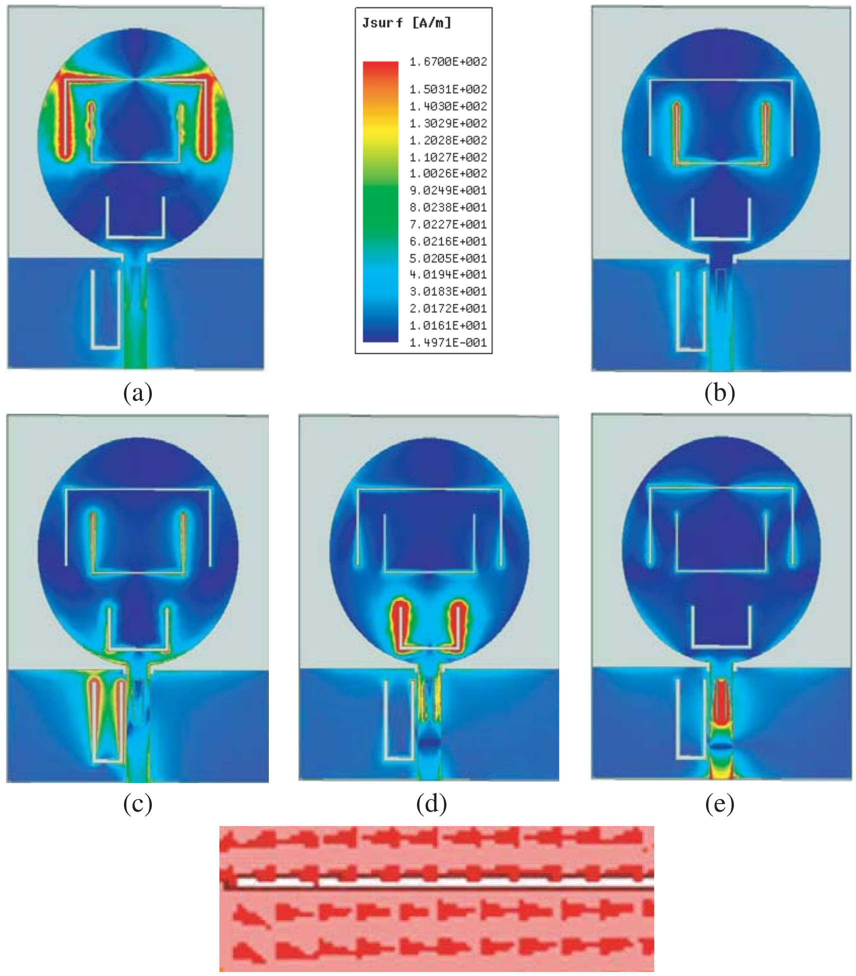


Figure 9. Surface current distributions at notched band center frequencies (a) 2.45 GHz (b) 3.5 GHz (c) 4 GHz (d) 5.5 GHz (e) 8 GHz and (f) direction of current on the slot at notch band.

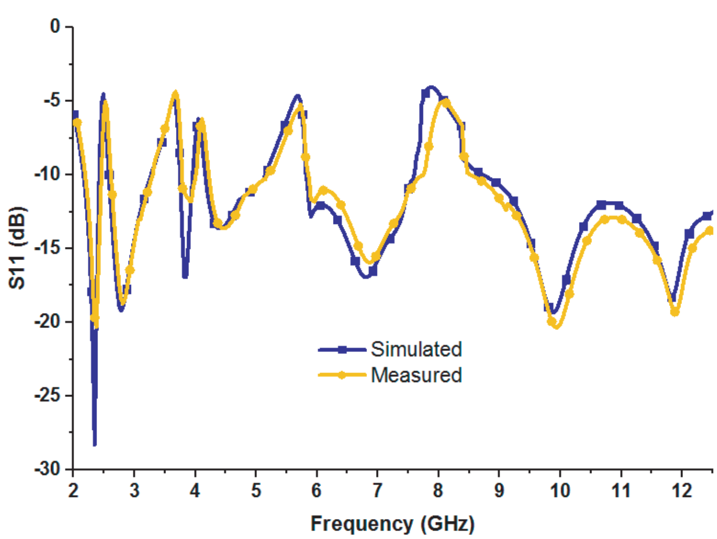


Figure 10. Comparison of experimental and simulated S-parameters of the proposed antenna.

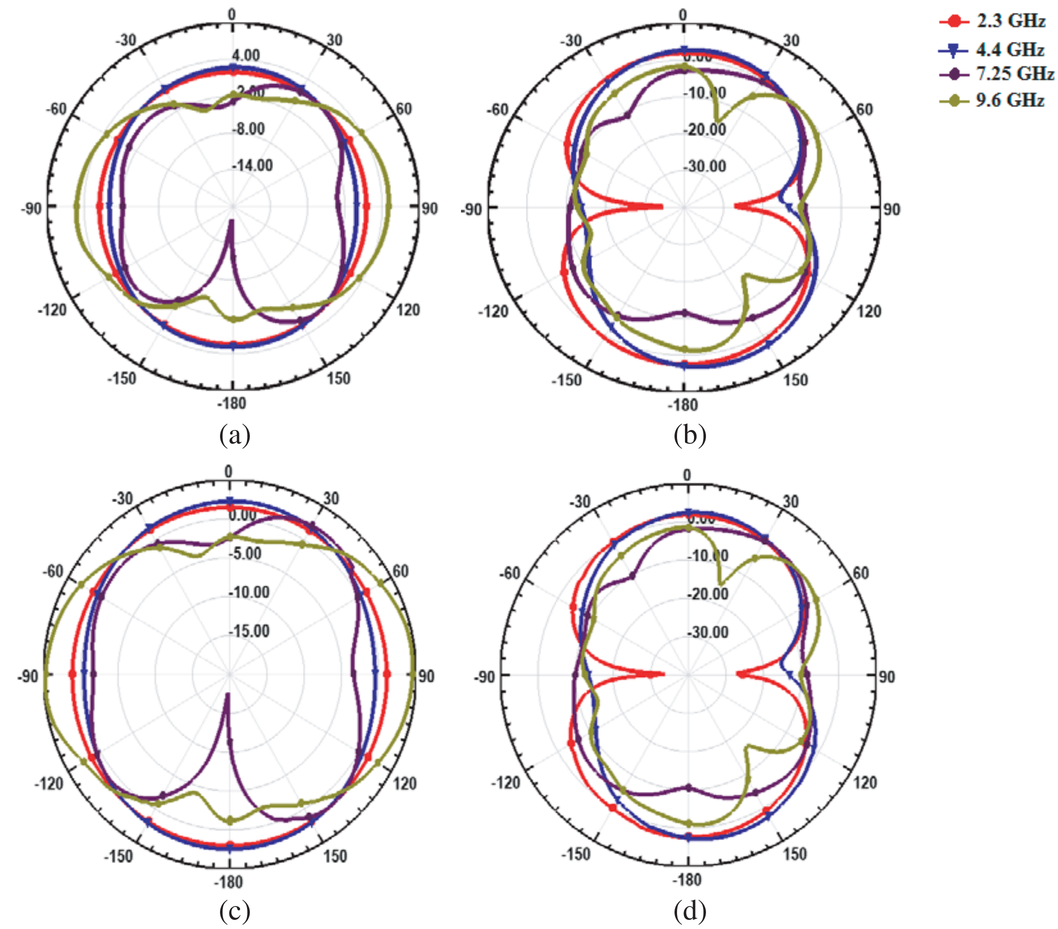


Figure 11. Radiation patterns of the proposed antenna, H-Plane (a) Simulated (c) Measured, E-Plane (b) Simulated (d) Measured.

Table 2. Gain suppression and radiation efficiency at notch bands.

Notch Band (GHz)	**Center Frequency (GHz)**	**Gain Suppressed (dB)**	**Radiation Efficiency (%)**
2.4–2.6	2.45	7	35
3.3–3.75	3.5	7.5	36
3.9–4.2	4	9	32
5.15–5.87	5.5	10	47
7.75–8.5	7.7	11.5	35

bands, S_{11} is more than -5 dB. The S-parameters of the prototype antenna are measured using Anritsu MS2037C vector network analyzer.

The simulated and measured E-plane (YZ) and H-plane (XZ) radiation patterns of the proposed antenna at passband frequencies 2.3 GHz, 4.4 GHz, 7.25 GHz, and 9.6 GHz are shown in Figure 11. The measured radiation pattern has good agreement with simulated ones. The far-field radiation pattern in the E-plane is the same as that of the dipole antenna (figure of eight), and the H-plane pattern is almost omnidirectional which is desired to receive the signal from all directions.

Figure 12 displays simulated and measured peak gains with and without notch function. It is found

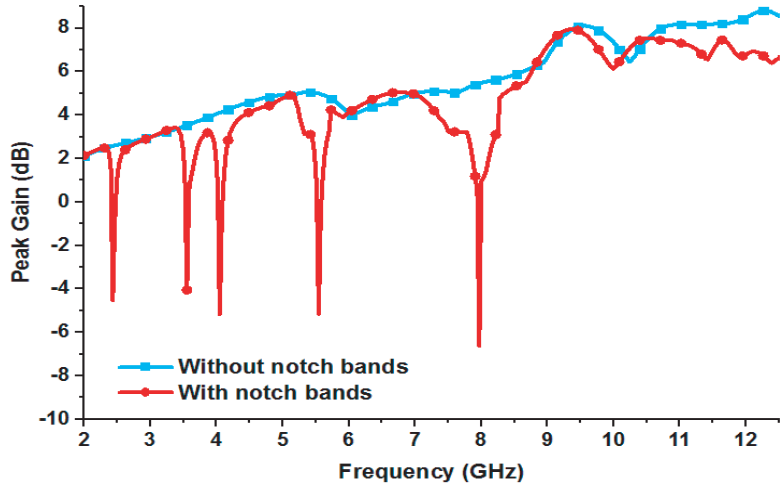


Figure 12. Peak gain of proposed antenna with and without notch bands.

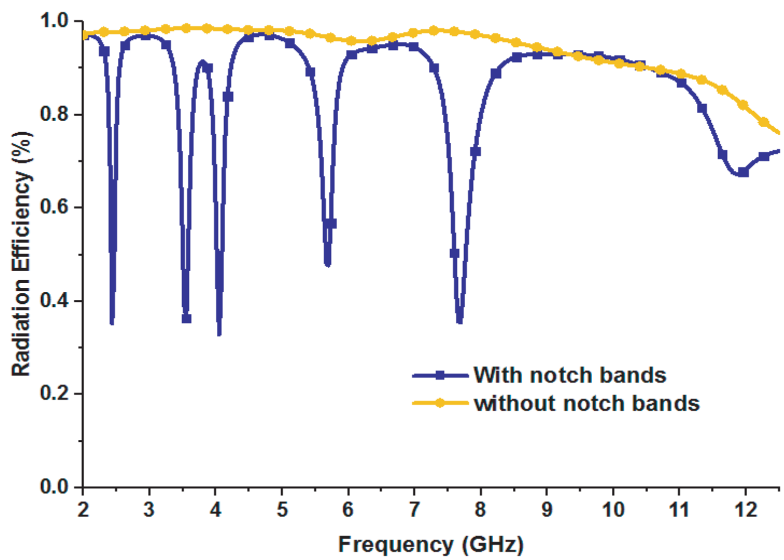


Figure 13. Radiation efficiency with and without notch bands.

that the measured peak gain ranges from 2 to 7.3 dB. Also, the peak gain of the proposed antenna is drastically dropped to below 0 dB at the designed notch bands. Figure 13 shows the simulated radiation efficiencies of the proposed antenna with and without notch bands. It can be observed that at the passband frequencies the efficiency is above 90%, but at notch bands, it is dropped remarkably to below 50% as shown in Table 2. The results demonstrate that the proposed antenna can effectively minimize the frequency interference from the existing narrowband systems.

Antenna transfer function and group delay are measured using two identical UWB antennas mounted in two different orientations, i.e., face to face and side by side. Simulated and measured group delays and S_{21} are depicted in Figure 14. Nowadays, UWB antennas are used to transmit the digital data which are time varying pulses. We can understand the time domain features of the antenna by looking at the group delay and magnitude (S_{21}) response. Phase with respect to frequency must be linear to gain constant group delay because group delay is directly proportional to the derivative of the phase response. Pulse dispersion and pulse distortion are minimized by making group delay constant. This antenna shows the almost constant group delay in the passband, but in the notch bands variation is more than one nano second. So, the proposed antenna is suitable for transmit digital information.

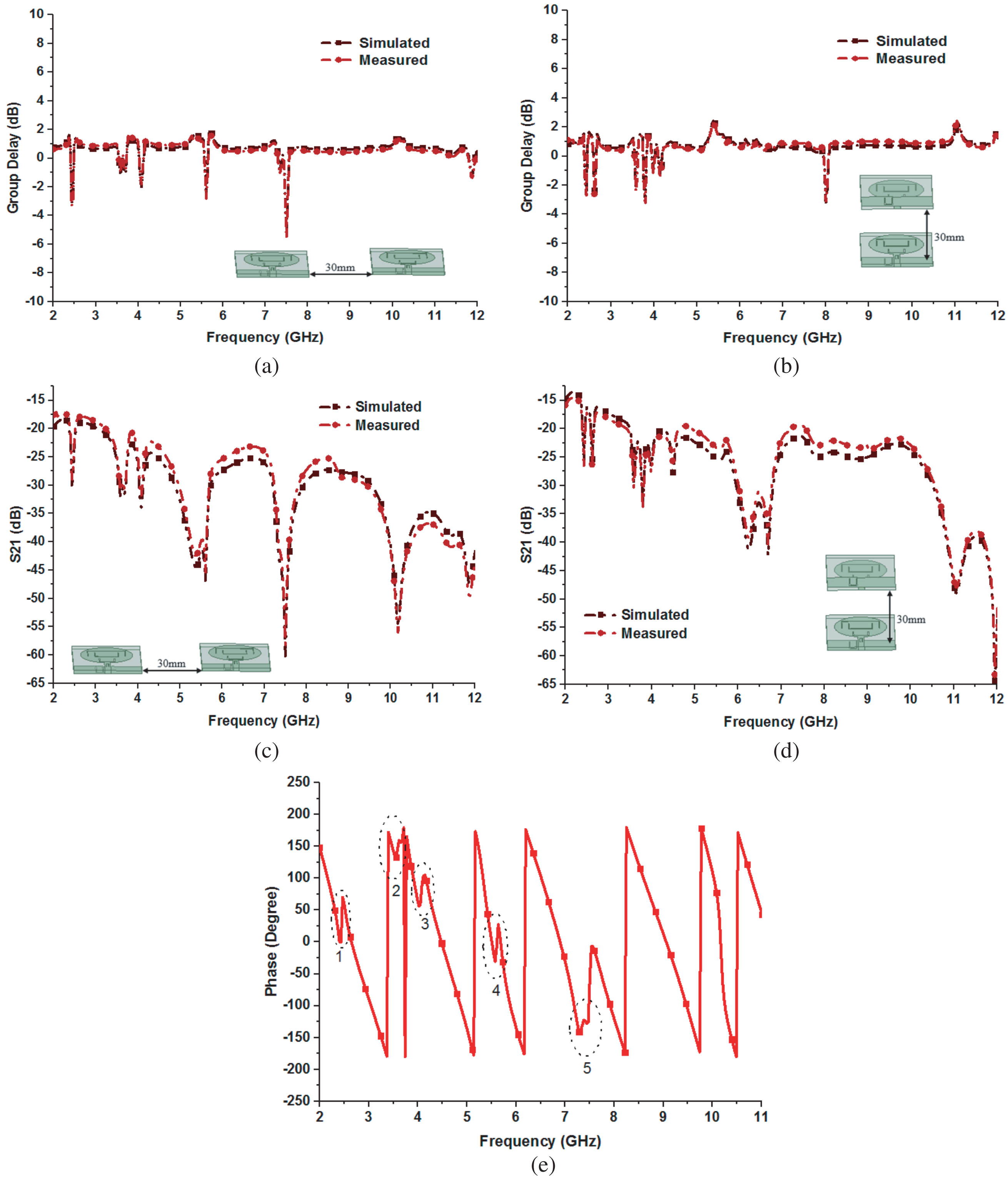


Figure 14. Simulated and measured Group Delay: (a) Side by Side (b) Face to Face and S_{21}: (c) Side by Side (d) Face to Face. (e) Simulated Phase with respect to frequency (1: at 2.4 GHz, 2: at 3.5 GHz, 3: at 4.1 GHz, 4: at 5.6 GHz, 5: at 7.5 GHz).

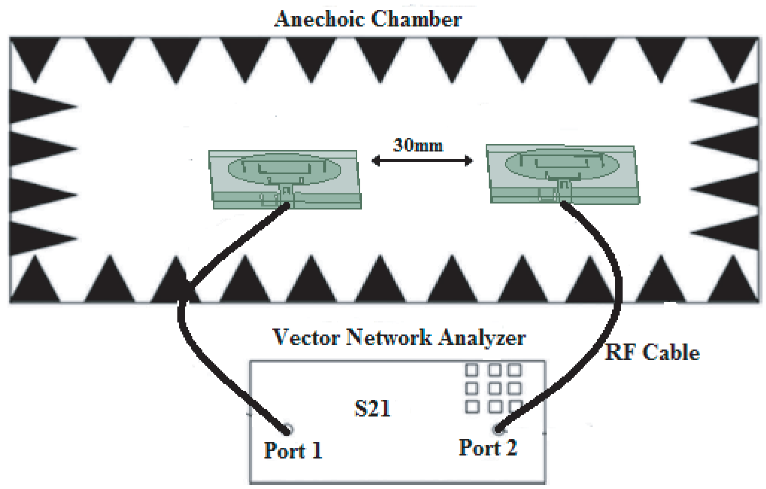


Figure 15. Experimental Setup of the proposed antenna system for measuring Group delay and Transfer function (S_{21}).

The setup of the proposed antenna system for measuring transfer function (S_{21}) is shown in Figure 15.

The proposed antenna performance is compared with existing literature in terms of size, bandwidth, peak gain, number of notch bands, and is given in Table 3. As observed from Table 3, the proposed antenna offers good impedance bandwidth, considerably high gain in the working band, and more notched bands than the other antennas mentioned in Table 3.

Table 3. Performance comparison of the proposed antenna with existed literature.

Ref. No	Size (mm^3)	Band width (GHz)	Peak Gain (dB)	No. of notched-bands
[14]	$50 \times 50 \times 1.575$	3–10.6	3	1
[12]	$30 \times 27 \times 1.6$	2.5–11.5	5	2
[9]	$25 \times 26 \times 1$	2.9–14.5	4.8	2
[19]	$53.25 \times 35 \times 0.78$	3.1–11.2	5.5	2
[15]	$50 \times 70 \times 1.575$	2.6–10.8	5	3
[18]	$50 \times 42 \times 1.6$	2.2–11	5.8	3
[11]	$31 \times 40 \times 0.51$	2.93–10.04	7.4	3
[20]	$42 \times 24 \times 1.6$	3–11	3.6	3
[17]	$38 \times 20 \times 0.508$	3–11	3.75	3
[13]	$34 \times 40 \times 1.6$	2.35–12	4.3	4
Proposed Antenna	$34 \times 46 \times 1.6$	2.15–12.5	8	5

4. CONCLUSION

An elliptical planar monopole antenna with five band-notched characteristics at IEEE 802.11b/g/n, Wi-MAX, WLAN, C-band satellite communication, and X-band satellite communication bands has been modelled, fabricated, and tested. The proposed antenna can operate in Bluetooth and UWB from 2.15–12.5 GHz. Penta band-notched properties are achieved by creating U-shaped slots on the radiating patch, feed line, and ground plane. The measured results have a good agreement with simulated ones. The proposed antenna has good radiation properties, high gain, efficiency, and capable of mitigating the frequency interference effectively from existing communication systems compared to the other models, which are mentioned in the literature. Due to Penta band-notched characteristics, the proposed design is well suited for wireless communication applications.

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