A Pentagonal Shaped Microstrip Planar Antenna with Defected Ground Structure for Ultrawideband Applications

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Abstract. *A new compact pentagonal microstrip patch antenna with slotted ground plane structure, developed for use in ultrawideband applications, is studied in this article.*
The proposed antenna is mainly constituted by a pentagonal shaped patch antenna, a defected ground plane structure, two stubs, and four slots to improve the bandwidth.
The designed antenna has an overall dimension of $30\times17.59\times1.6mm^3$, for WIMAX /WLAN/ WiFi/HIPERLAN-2 /Bluetooth /LTE /5G applications with a very large bandwidth starting from 2.66 GHz to 10.82 GHz (S_{11} < -6 dB). A parametric study of the ground plane structure was carried out to find the final and the optimal UWB antenna, and to confirm that the antenna has good performance and broader bandwidth. The proposed antenna prototype has been fabricated. The measured results indicate that the antenna has a good impedance matching.
The antenna has an electrically small dimension with a good gain, a notable efficiency, and a wide impedance bandwidth, which makes this antenna an excellent candidate for ultrawideband wireless communication, microwave imaging, radar applications, and the major part of the mobile phone frequencies as well.

Keywords

Defected ground plane; pentagonal shaped antenna; Ultrawideband (UWB); broadband antennas.

1.Introduction

Ultrawideband communication systems gain more interest since 2002 because of its wideband, low power consumption, high signal quality, and low profile [1]. Among the crucial components which determine the performance of the ultrawideband system is the antenna [2]. In the past decades, many antennas with various techniques of bandwidth enhancement have been proposed. Most of these techniques or antennas include entrenching different types of slots on the patch [2–5] or the ground plane[4, 6, 7]. Besides,   other different techniques have been proposed to achieve UWB operations, including the use of diverse shapes such as elliptical [8], semielliptical [9], octagonal [10], beveled rectangle [11], broken-heart[12], circular [13–15], or half-circle [16].

By embedding different elements to the antenna, one can also be enhanced the bandwidth of the conventional patch antenna such as the parasitic elements [5,17], stubs [4], splint ring resonator (SRR) [15,16], steps [3]or additional patch [13].

The impedance bandwidth can be optimized by adjusting the feed gap and the plate width [18], by shifting from the center of the substrate the radiating plate and the feed line [19], or by using metamaterial (MTM) [20].

In this article, a new ultrawideband antenna for UWB applications is studied; the suggested antenna consists of a pentagonal shaped patch antenna, a microstrip feed line shifted from the center of the defected substrate, a defected ground plane structure, two stubs, and four slots to enhance the bandwidth.

With the assistance of the full-wave electromagnetic solver ANSYS HFSS the antenna was optimized. Furthermore, a prototype of this antenna is fabricated and tested. The measured and simulated result of reflection coefficient S_{11} and the radiation pattern in the E and the H planes are presented and discussed. It is found that both results are to be in good agreement.

This article paper is organized as follows: Section 2 gives a detailed description of the geometry of the antenna, the design procedure, and the effect of the defected ground structure. Section 3 analyzes the different obtained results of the proposed antenna. Finlay, section 4 gives a conclusion of the study.

2.Antenna design and analysis

2.1 Antenna Geometry

Figure 1 depicts the geometry layout of the suggested pentagonal shaped with defected ground plane patch antenna. The antenna uses the FR4 as substrate material having a dielectric constant of 4.4, a loss tangent of 0.02, and a thickness of 1.6 mm.

As illustrated in Fig. 1, the proposed antenna is composed of a radiating pentagonal shaped patch, a defected ground plane, two stubs etched in the ground, three identical slots in the top of the radiating patch, and an inverted L slot in the lower-left corner of the patch. The pentagonal patch antenna is located on the top of the substrate. While on the bottom, we found the defected ground structure (DGS). The overall dimension of the proposed antenna is 30 × 17.59 mm^2. An extensive simulation was carried out to optimize the design parameters of current research work using the electromagnetic simulator HFSS. The optimized dimensions are listed in Tab.1
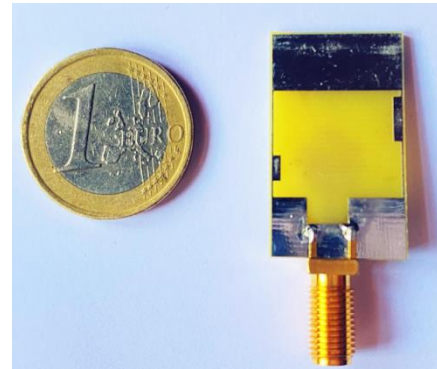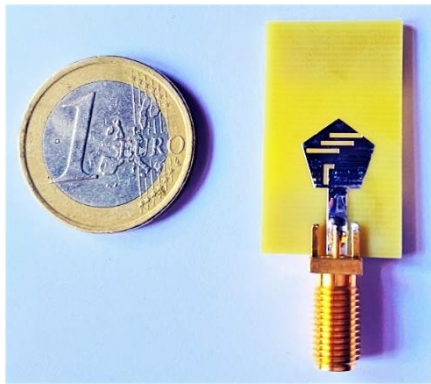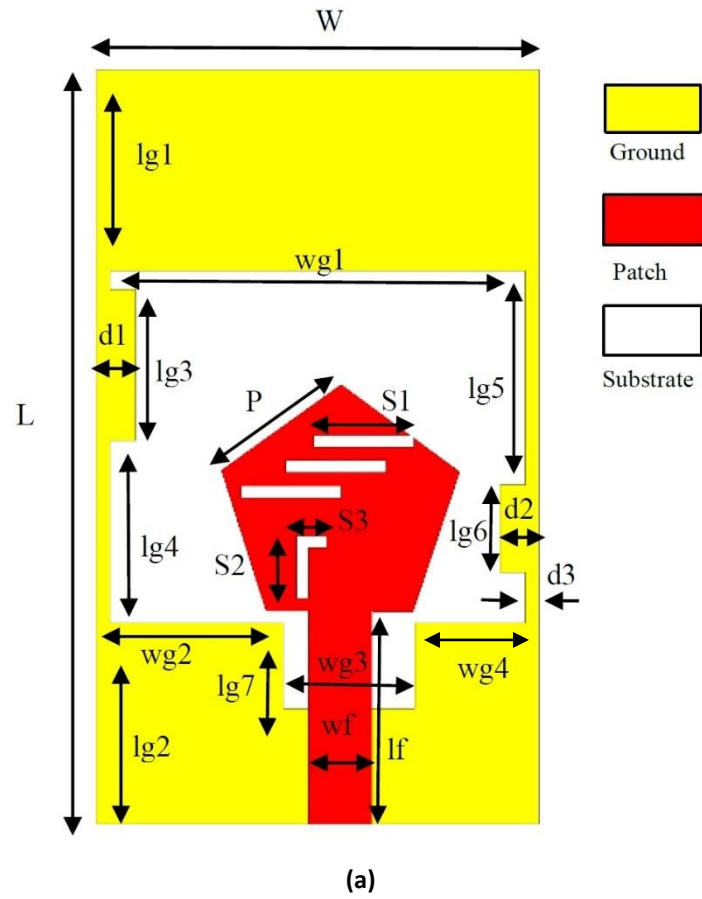
(a)

(b)

(c)

Fig. 1. The proposed ultrawideband antenna.

(a) The geometry, (b) Front view and (c) Back view.

2.2 Design Procedure

In this section, four design steps are used to describe in detail the design procedure of the proposed antenna. Fig. 2 depicts the realization for current research work with the help of the four steps. The simulated reflection coefficient curve from the first step (Ant. 1) to the last one (Ant. 4) is presented in Fig. 3.

As illustrated in Fig. 2, in the first stage, a square radiating patch antenna [named Ant. 1] is designed. The length of the square is chosen approximately equal to half a wavelength at the resonant frequency and can be calculated using the equations below:

$$f_s = \frac{C}{2L_s\sqrt{\varepsilon_{reff}}} \qquad (1)$$

$$\varepsilon_{reff} \approx \frac{\varepsilon_r + 1}{2} \qquad (2)$$

Where C is the speed of light in vacuum, ε_r is the relative permittivity, ε_{reff} is the effective relative permittivity, L_s the length of the square, and f_s *is* the fundamental resonant frequencies.
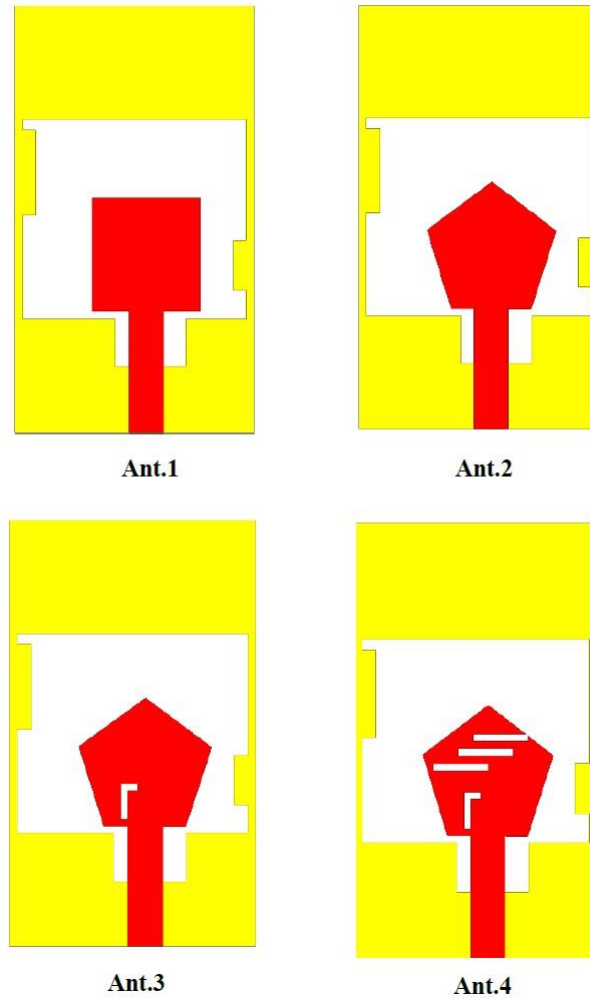

Fig. 2. The antenna evolution steps to realize the proposed UWB antenna.

In the second stage, and for enhancing the antenna bandwidth, the square shape of the radiating patch is changed into a pentagonal shape where the number of straight lines is five, and the length is P [named Ant. 2]. It also provides additional resonance. In the third stage, and in order to improve the impedance matching and to provide a wider impedance bandwidth, an inverted L shaped slot was embedded in the radiating patch [named Ant. 3].

Tab. 1. Optimized dimensions of the proposed pentagonal shaped microstrip patch antenna.

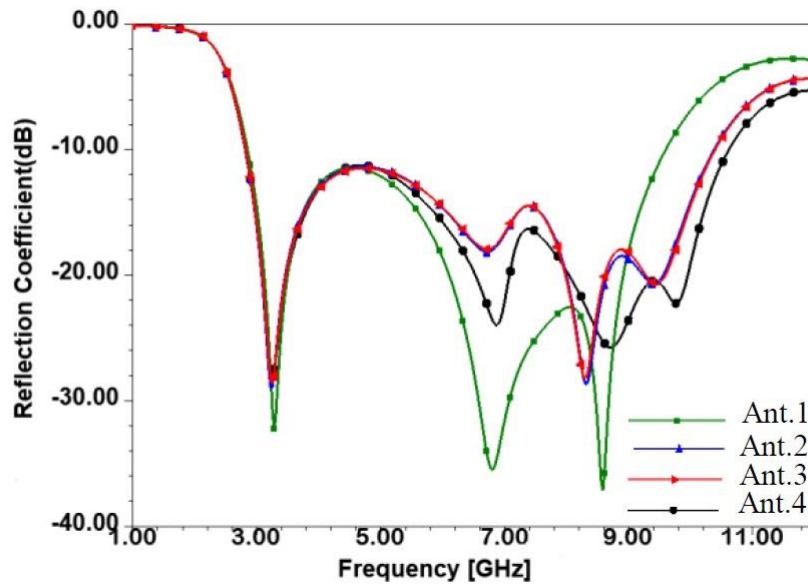| Parameter	W	L	lg1	lg2	lg3	lg4	lg5
Value(mm)	17.59	30	8	8	6	7.25	8.5
Parameter	lg6	lg7	wg1	wg2	wg3	wg4	lf
Value(mm)	3.5	3.4	16.5	6.9	5.2	4.4	8.47
Parameter	wf	P	S1	S2	S3	d1	d2
Value(mm)	2.5	5.84	3.81	2.5	1.2	1.59	1.5

Fig. 3. The Simulated reflection coefficient for different stages (Ant. 1 to Ant. 4).

A broaden bandwidth range is obtained by adding three slots with the same dimension and different positions in the top of the pentagon radiating patch of Ant. 3 [named Ant. 4].

The obtained reflection coefficient for the optimized set of the different stages of the antenna is presented in Fig.3. The simulated impedance bandwidths (S_{11} < −6 dB) are about 7.42 GHz for Ant.1 (from 2.67 to 10.09 GHz), 8.3 GHz for Ant.2 (from 2.5 to 11.08 GHz), and 8.4 GHz for the third antenna Ant.3 (from 2.6 to 10.08 GHz). Moreover, it is seen that Ant.4 has a broader bandwidth from 2.66 to 10.8 GHz with a total bandwidth of 8.14 GHz. One can conclude that the proposed antenna can cover in totality the required bandwidths of the FCC UWB standards.

2.3 Effect of the Defected Ground Structure

Knowing that the ground plane has an essential role in widening the bandwidth of antennas, in this section, and to display the advantage of the defected ground plane and to choose the most suitable ground structure to obtain an ultrawideband antenna; four design steps were carried out. Fig.4 illustrates the design procedure of the ground plane by using the four design stages with the same radiating pentagonal patch antenna with slots.

Figure.5 illustrates the reflection coefficient for the different ground plane steps (from Ant.a to Ant.d). It can be seen that the reflection coefficient for Ant.a by using a full ground plane only

one resonant frequency is obtained. The resonance frequency is equal to 7.97 GHz with a reflection coefficient of a -32 dB and a frequency band of 1.29 GHz ($S_{11} < -6$ dB).

In the second stage (Ant.b), other resonance frequencies are obtained by cutting a rectangle with a dimension of 16.5×14 mm^2 from the ground plane. To enhance the bandwidth of the previous antenna, another rectangle with a dimension of 5.2×3.4 mm^2 is removed from the ground plane; the obtained antenna (Ant.c) provides bandwidth from 2.52 GHz to 10.91 GHz. Finally, to obtain the desired ultrawideband antenna (Ant.d), two rectangular stubs with a dimension of 6×1 mm^2 and 3.5×1 mm^2 are embedded in the higher left and the lower right of the first rectangular cut respectively.
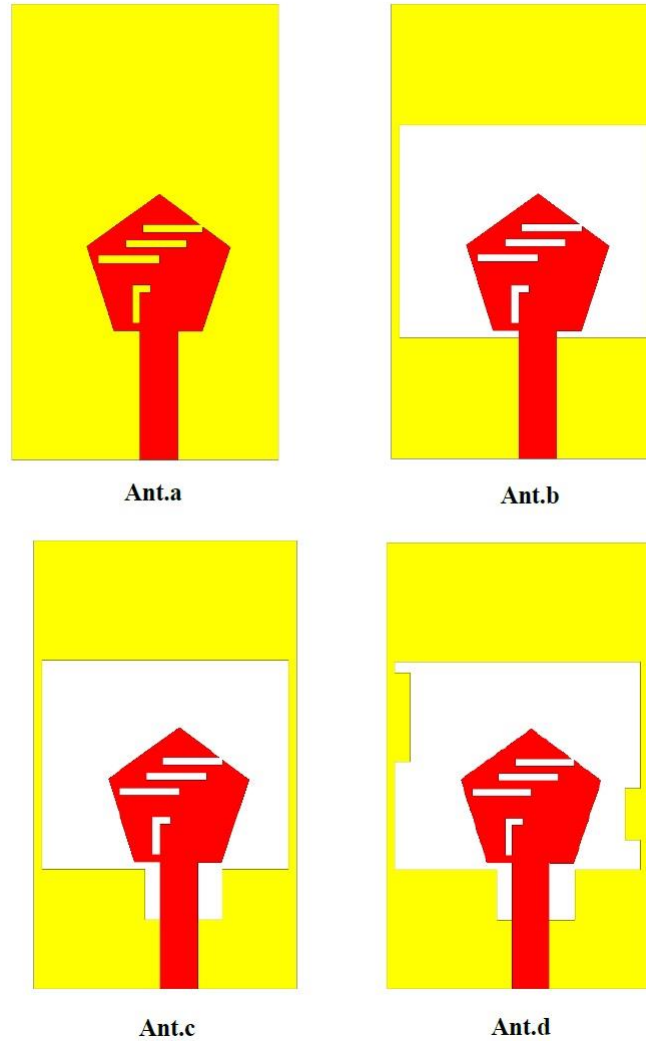

Ant.a

Ant.b

Ant.c

Ant.d

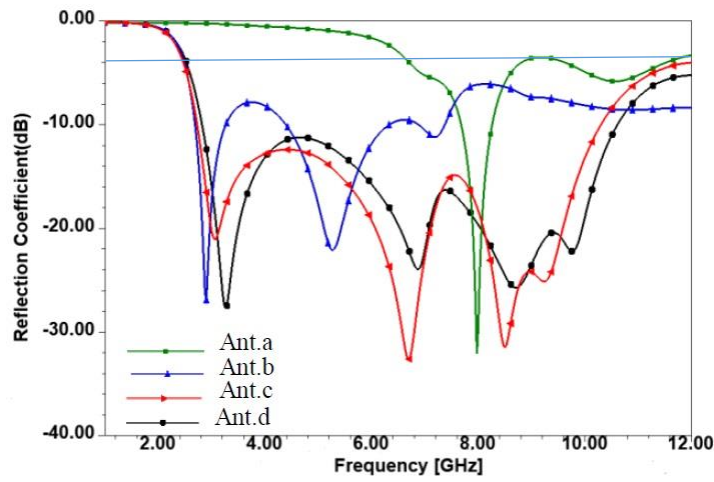**Fig. 4. Ground plane evolution stages of realizing the proposed UWB antenna.**
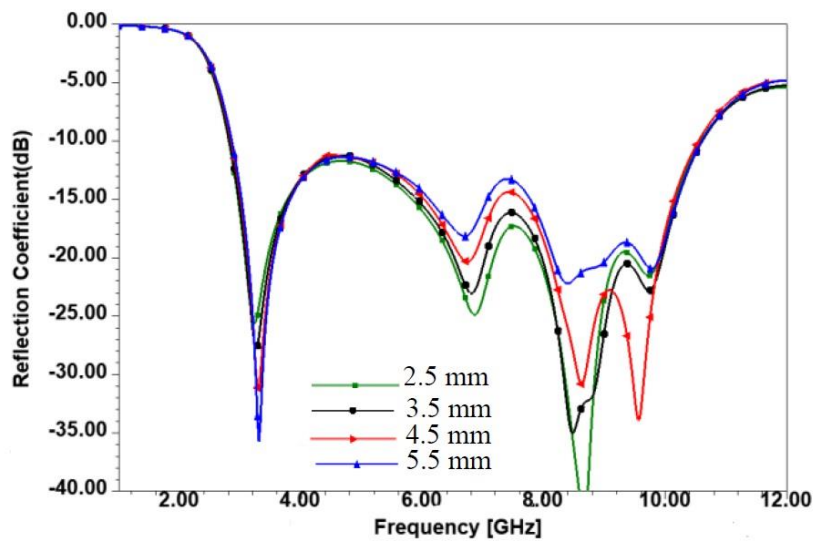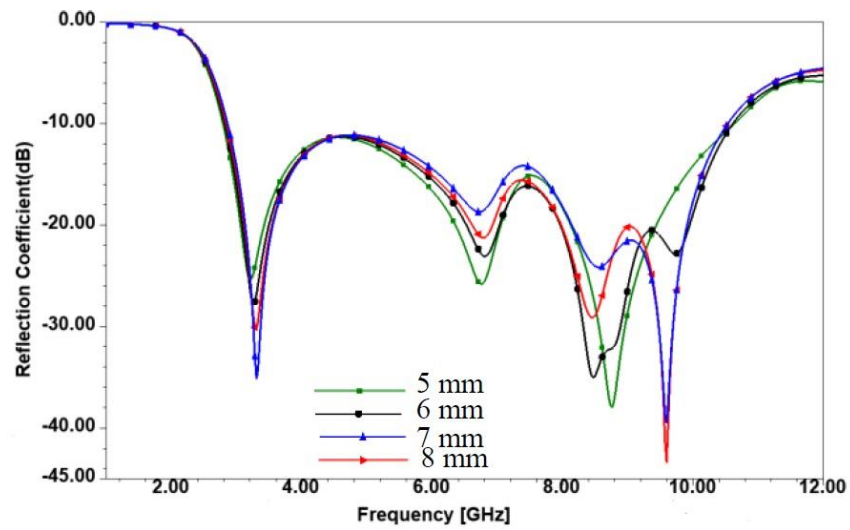
Fig. 5. Simulated reflection coefficient for different stages (Ant.a to Ant.d).

2.4 Effect of Varying the DGS Dimensions

This segment is explained in order to investigate the response of the bandwidth by employing some critical parameters in the ground plane. The key parameters of the proposed antenna are lg6, lg3, wg1, wg3, and lg7 considered to optimize values; the simulated reflection coefficient curve for different values of each parameter is shown in the figures below.
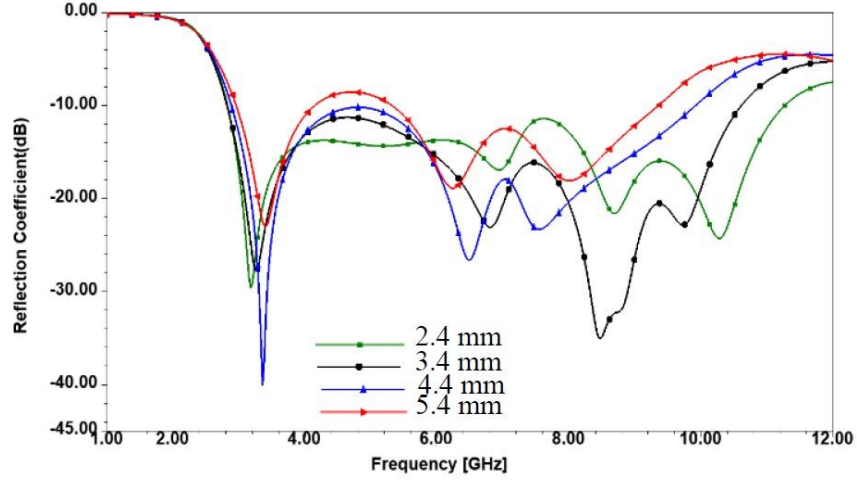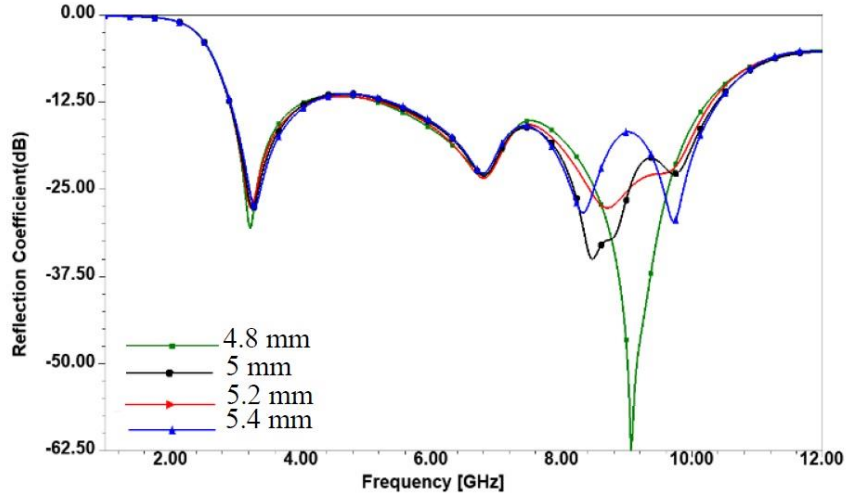

(a)

(b)
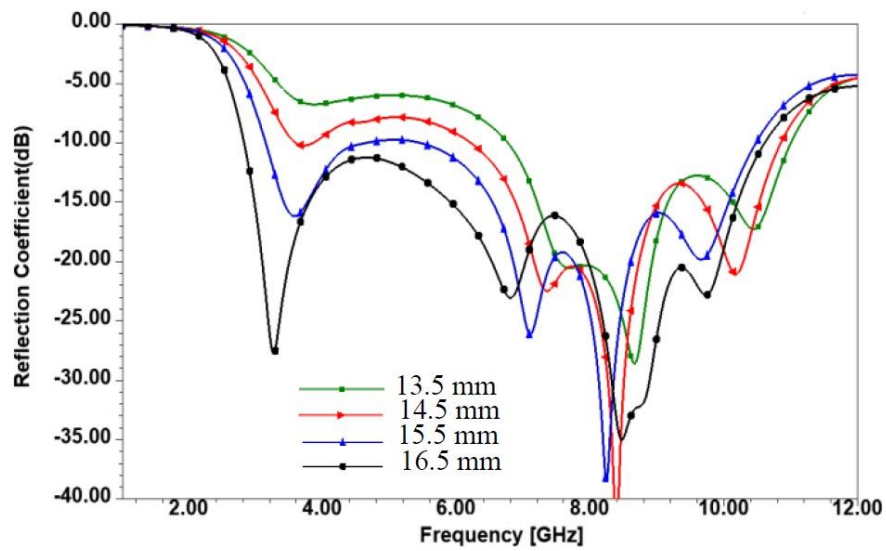
(c)

(d)

(e)

Fig. 6. Simulated reflection coefficient for a different set of values of (a) lg6, (b) lg3, (c) wg1, (d) wg3, and (e) lg7.

Figure 6 illustrates a parametric study of the defected ground plane of the proposed antenna. This study is built on the antennas structures presented in Fig.1 and the values given in Tab.1. Fig. 6(a) and Fig. 6(b) illustrates the effect of varying the lengths of the first and the second stubs lg6 and lg3, respectively, on the reflection coefficient. It is seen that the increase in lg6 or lg3 affects the higher and medium frequency bands, while the lower frequency response is kept constant. Figure. 6(c) shows the effects of the width of the first rectangular cut on the reflection coefficient when wg1 varies from 13.5 to 16.5 mm. From this figure, it can be seen that the decrease in wg1 increases the bandwidth on the higher frequency side for all the frequency bands. By varying the width and the length of the second rectangular cut wg3 and lg7respectively, it can be concluded that by increasing the width wg3 the bandwidth decrease notably (Fig.6 (d)), and the variation of the length lg7 (Fig.6(e)) affect only the third resonant frequency band that's shifting towards the lower frequency while the other resonant frequencies bands are unchanged.

3. Results and Discussion

3.1 Reflection Coefficient

The reflection coefficient is measured with Rohde and Schwarz ZVB20 vector network analyzer, which has a frequency range limited to 20 GHz.

Figure.7 displays the simulated and measured reflection coefficients of the presented UWB antenna. We notice that the simulated result obtained by HFSS shows a bandwidth from 2.66 to 10.80 GHz (at -6 dB), whereas, the obtained measured bandwidth is from 2.66 to 10.45 GHz (at -6 dB). The reason for this difference between the simulated and measured results is due to the effect of SMA connector soldering and fabrication tolerance.
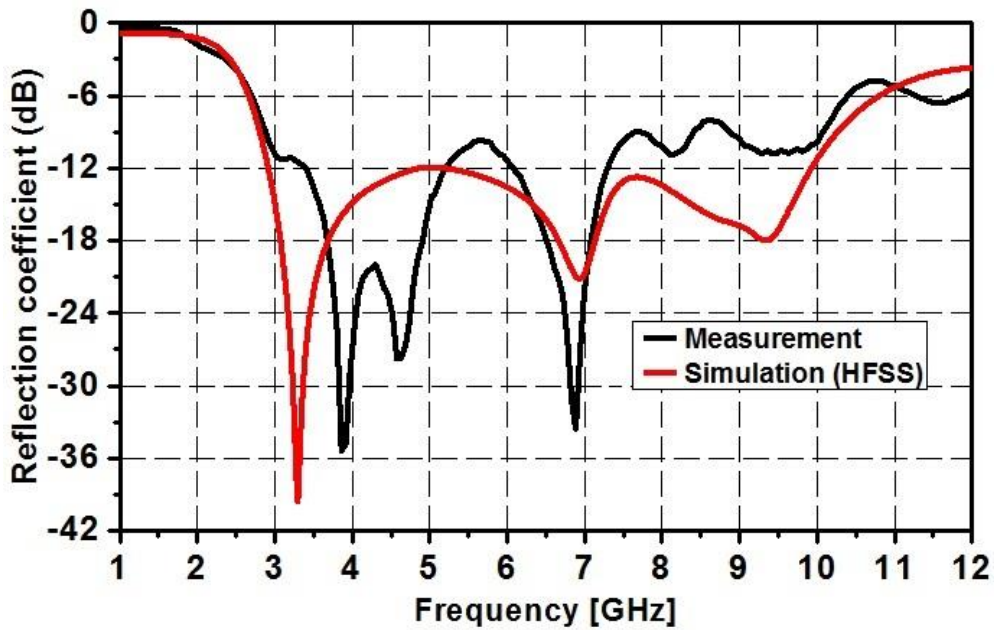
Fig. 7. The simulated and measured reflection coefficient of the proposed antenna.

3.2 Surface Current Distribution

Figure.8 displays the surface current distributions on the whole proposed UWB antenna, including the defected ground plane at different resonant frequencies, in order to further demonstrate the ultrawideband operation mechanism.
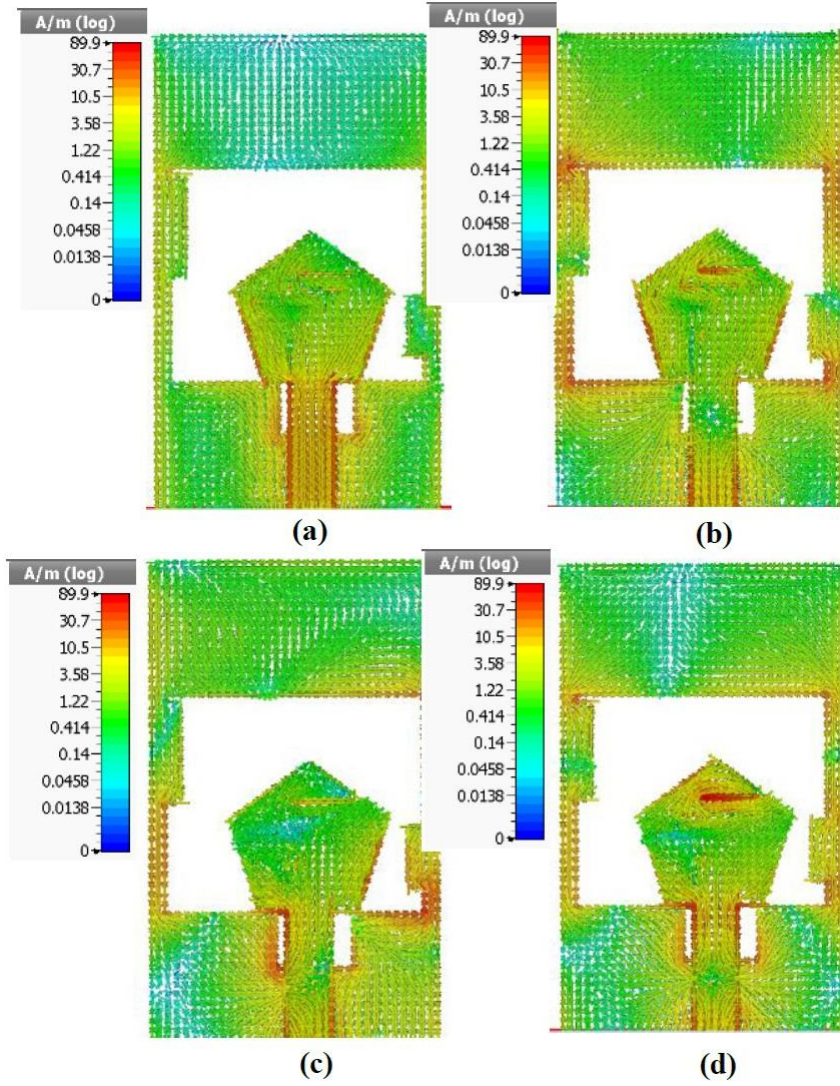
Fig. 8. Simulated surface current distributions of the proposed antenna at (a) 3.8 GHz, (b) 4.5 GHz, (c) 6.8 GHz, and (d) 8 GHz.

One can observe that the current has different distributions along the surface of the antenna in different frequency bands. Fig. 8(a) shows that at 3.8 GHz, the current is involuntarily flowing the pentagonal radiating patch and especially on the bottom. The current distributions at frequency 4.5 GHz (Fig. 8(b)) are found to be more concentrated in the two edges of the left and right ground plane near the first rectangular cut and the first stub. The current distributions in the case of the frequency 6.8 GHz (Fig. 8(c)) divulge that the surface current density is maximum near the second rectangular cut and the second stub. Concerning the last figure (Fig.8(d)), it depicts the current distributions at the frequency 8 GHz, and it illustrates that the current distributions are more concentrated around the top slots.

3.3 Radiation Patterns, Gain and Efficiency of the Antenna

The radiation patterns of the proposed antenna at different bands in E-plane ($\varphi = 0\circ$) and H-plane ($\varphi = 90\circ$) areas at different resonance frequencies are simulated, measured and illustrated in Figs. 9(a)-(d) respectively.

Figure.9 (a) and Fig.9 (b) illustrates the radiation pattern of the antenna at 3.8 GHz and 4.5 GHz, respectively. It can be seen that the pattern is omnidirectional in these two frequencies. While, in Fig.9(c) and Fig.9 (d), which represents the radiation pattern at 6.8 GHz and 8 GHz, respectively, we remark a nearly omnidirectional radiation pattern since the high frequencies are more affected by variation in relative permittivity of the substrate.
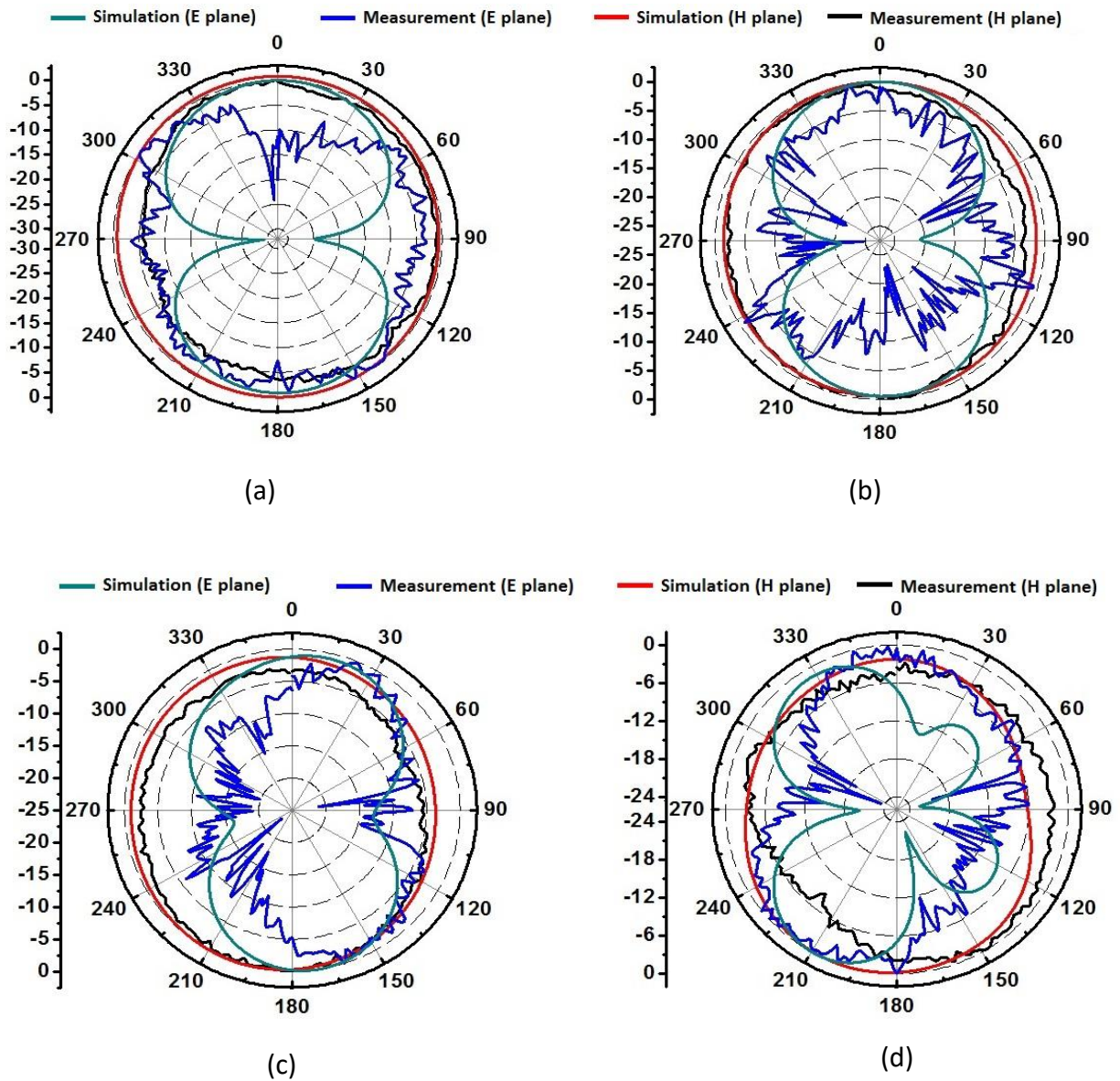

(a)

(b)

(c)

(d)

Fig. 9. Simulated and measured radiation patterns of the proposed UWB antenna at frequencies (a) 3.8 GHz, (b) 4.5 GHz, (c) 6.8 GHz, and (d) 8 GHz.

Figure.10 illustrates the radiation efficiency and the gain of the proposed UWB antenna. From this figure, we notice that the efficiency varies between 89.21% and 99.96% in the whole frequency band, and the maximum obtained gain is 3.38 dB. A comparative study of the suggested antenna with other UWB antennas in terms of size, totally occupied size, type of substrate, and the frequency of operation have been summarized in Tab.2. From this comparative study table, it is evident that the proposed ultrawideband antenna occupies the smallest area, use an inexpensive substrate, and cover a large bandwidth, knowing that it has a simpler geometry compared to other cited designs.
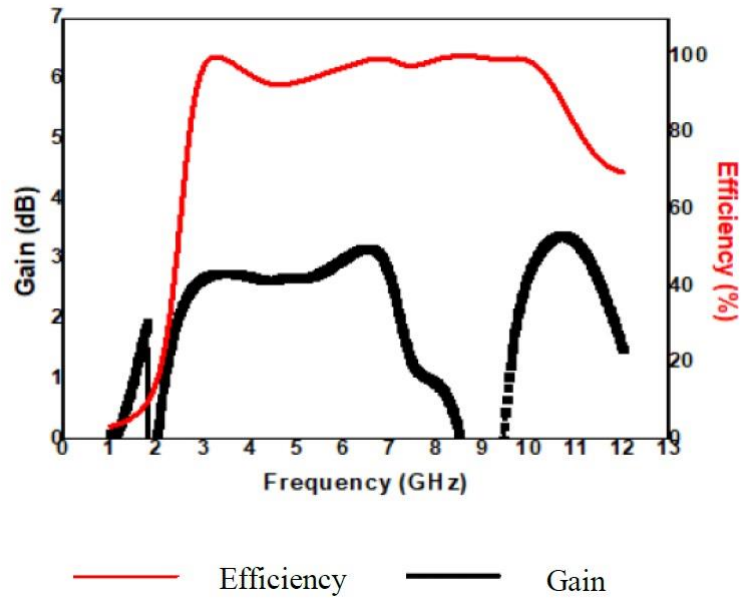

Fig. 10. Gain and radiation efficiency for the proposed antenna.

Tab. 2.   A comparison of the proposed antenna with other related ultrawideband antennas.

Related works	Size (mm³)	Bandwidth(GHz)	Substrate
[4]	40× 40×1.9	3.18 - 11.50	Taconic RF-30(ε_r =3, $tan\delta$ = 0.0014)
[7]	50× 50×1.6	3.00 - 10.50	FR4(ε_r =4.4, $tan\delta$ = 0.02)
[15]	25× 25×0.762	3.10 - 10.60	RO6003(ε_r =3, −)
[18]	29× 20.5×1.6	2.96 - 19.00	FR4(ε_r =4.5 , $tan\delta$ = 0.02)
Proposed Antenna	30 × 17.59×1.6	2.66 - 10.80	FR4(ε_r =4.4 , $tan\delta$ = 0.02)

4.Conclusion

In this article, a compact and miniature ultrawideband antenna is proposed. The presented antenna has a broader bandwidth from 2.66 to 10.88 GHz. The simulated results show that the defected ground plane, slots, and stubs are critical factors for improving the bandwidth of the proposed antenna. The proposed antenna was designed, fabricated and tested. The measured -6 dB reflection coefficient bandwidth ranging from 2.66 à 10.45 GHz.

In conclusion, the antenna achieves a broad impedance bandwidth, the small size, the stable radiation patterns, and the higher radiation efficiency. It is demonstrated experimentally that the proposed antenna can cover all the UWB frequency band. Therefore, the proposed antenna can be the best candidate for WIMAX /WLAN/ WiFi/HIPERLAN-2 /Bluetooth /LTE /5G applications.

ACKNOWLEDGMENT

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