

Superformula-Based Compact UWB CPW-Fed-Patch Antenna With and Without Dual Frequency Notches

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Abstract — This paper presents two new designs of UWB coplanar waveguide (CPW)-fed-patch antennas operating in the FCC frequency band (3.1-10.6 GHz). The first design uses the superformula to produce a circular patch with sawtooth-like circumference. As compared to a regular circular patch antenna whose diameter is 25 mm, the proposed circular patch has a smaller diameter of 18.2 mm. Moreover, the proposed antenna covers the entire FCC band unlike a regular circular patch of the same radius. The second design introduces two frequency notches at 3.3-3.8 GHz (WiMAX) and 5-5.9 GHz (WLAN) using two arc shaped circular slots etched on the circular patch and a split-ring resonator (SRR) that is placed on the opposite side of the substrate. Measurements and simulations using HFSS show that the return loss is better than 10 dB across the band except at the two notch locations in Design II. Results are also presented for the radiation pattern and peak gain of both designs. Each of the proposed antennas has a compact size of 24 mm x 19 mm on a 1.5 mm Rogers Substrate ($\epsilon_r=3.85$).

Index Terms — Coplanar waveguide, frequency notch, SRR, superformula, UWB.

I. INTRODUCTION

Ultra-wideband antennas (UWB) have attracted much attention in the past few years because they cover a wide frequency spectrum which can be utilized for multi-applications. This makes them very appealing especially for broadband wireless applications such as mobile communications, short range radar, medical imaging, etc. The Federal Communications Commission (FCC) has reserved the frequency band between 3.1 and

10.6 GHz to be an unlicensed band in which UWB antennas are the most appropriate types of antennas [1].

To be compatible with monolithic microwave integrated circuits, UWB antennas have mainly employed microstrip or coplanar waveguide (CPW) feeds. However, CPW has several advantages over microstrip in terms of easier integration with active and passive elements, lower frequency dispersion, the extra design freedom through the ability to vary the characteristic impedance and phase constant by changing the slot and strip widths, and avoiding the excessively thin, and therefore fragile, substrates as in microstrip line [2, 3].

Gielis, in the year 2003, proposed what is known as the superformula which is basically a generalization of the super-ellipse formula [4]. It has six different parameters which when properly selected can produce many complex shapes and curves that are found in nature. The superformula has been used by Simone *et al.* [5] to produce dielectric resonator antennas of different shapes. It has also been used by Bia *et al.* to produce supershaped lens antennas for high frequency applications [6]. Paraforou [7] applied the superformula to get different patch antenna shapes. The same formula has also been used by Naser and Dib [8] to design a compact UWB microstrip-fed patch antenna.

More recently, the superformula was used by Omar *et al* [9] to design UWB CPW fed patch antenna that operates in the FCC band (3.1-10.6 GHz). The patch shape proposed in [9] was circular with sawtooth-like circumference, as shown in Fig. 1, which is used to replace the conventional circular patch antenna [10, 11]. The use of sawtooth patch allows for a reduction of the patch diameter from 25 mm to 18.2 mm without affecting

the UWB performance. It also allows for an increase in bandwidth. However, no measurements were provided in [9] to verify the design and only simulation results for the return loss and radiation pattern were provided. Moreover, [9] proposed one antenna design only that does not have any frequency notches.

In this paper, we provide measured results for the return loss and group delay of the antenna proposed in [9]. These results are used to verify the design through comparing measurements with HFSS [12] simulations. Simulated results are also provided for the radiation pattern and peak gain across the FCC band. The choice of the circular patch with sawtooth-like circumference was motivated by the fact that repeated patterns on the radiating element are expected to increase the bandwidth as is the case of fractal geometries [13-15].

Moreover, in this paper, the design in Fig. 1 is modified to include two frequency notches that will exclude the WiMAX (3.3-3.8 GHz) and WLAN (5-5.9 GHz) bands from the UWB antenna band [11, 16, 17]. These two notches are generated by etching two arc-shaped radiating slots in the circular patch, and adding a split ring resonator (SRR), as shown in Fig. 2. Measured and simulated results are presented for the return loss and group delay of both designs. Simulation results are also presented for the radiation pattern and peak gain.

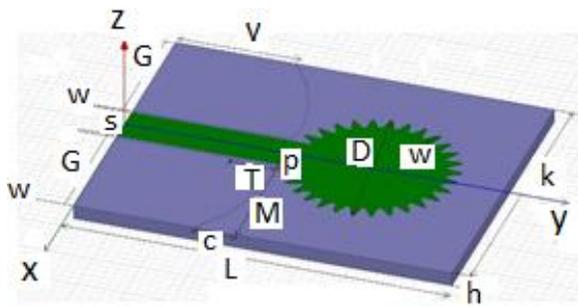


Fig. 1. 3-D view of the UWB antenna (Design I). ($\epsilon_r=3.85$, $\tan\delta=0.0088$, $h=1.5$ mm, $S=4.532$ mm, $W=0.34$ mm, $L=40$ mm, $K=32.4$ mm, $G=13.6$ mm, $V=12.7$ mm, $M=13.5$ mm, $C=4.25$ mm, $T=4.76$ mm, $P=1.94$ mm, $D=18.2$ mm).

Section II presents the superformula and its parameters that were used to produce the designs of Figs. 1 and 2. Section III shows our results for the UWB antenna of Fig. 1 (Design I). Section IV shows our results for the antenna of Fig. 2 (Design II) which has two frequency notches. Section V produces reduced size versions of our two antenna designs by simply shortening the length of the feeding CPW and reducing the lateral and longitudinal extents of the substrates. A comparison is then carried out in this section in terms of size between our designs and several other UWB antennas available in the literature.

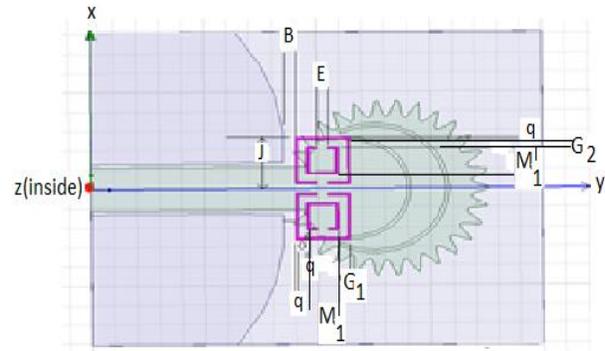


Fig. 2. Top view of the notched UWB antenna with two arc-shaped slots and one SRR (Design II). The SRR is at $z=-1.5$ mm (i.e., at the bottom side of the substrate), while the feed and patch are at $z=0$. ($J=5.35$ mm, $q=0.25$ mm, $O=0.8$ mm, $M_1=2.55$ mm, $G_1=1.05$ mm, $B=1$ mm, $E=1$ mm, the other dimensions are the same as in Fig. 1).

II. ANTENNA DESIGN

The superformula has six parameters: n_1, n_2, n_3, m, a, b . It is given by [4]:

$$r = \left[\frac{\cos\left(\frac{m\theta}{4}\right)}{a} \right]^{n_2} + \left[\frac{\sin\left(\frac{m\theta}{4}\right)}{b} \right]^{n_3} \right]^{-\frac{1}{n_1}} \quad (1)$$

Each of the parameters a and b are chosen to be 1 to ensure symmetry of the antenna patch. The parameters n_1, n_2 and n_3 are positive real numbers. The parameter m determines the number of points, corners, sectors, or hollows fixed on the shape and their spacing, while n_2 and n_3 determine if the shape is inscribed or circumscribed in the unit circle. In our design, the chosen parameters are $a = b = 1$, $m = 30$, $n_1 = n_2 = n_3 = 5$ [9]. These will generate the circular patch shapes with sawtooth-like circumference shown in Fig. 1 and Fig. 2.

The two antenna designs of Fig. 1 and Fig. 2 were fabricated on Rogers substrate ($\epsilon_r=3.85$, loss tangent=0.0088) of 1.5 mm thickness. The overall dimension for the antenna in each design is 40 mm x 32.4 mm. This will be optimized in Section IV. The feeding CPW has a center conductor width of 4.53 mm and a slot width of 0.34 mm to yield a 50Ω impedance. Each slot is slowly tapered out to increase the characteristic impedance of the CPW as it approaches the patch for better matching. In addition, in both designs, the ground plane has been curved for better matching. In Fig. 1, G and M are not equal due to the slot taper.

The diameter of the patch in both designs is $D=18.2$ mm, while the optimal diameter of a conventional circular patch operating in the FCC band (3.1-10.6 GHz) is 25 mm [11]. This represents about 30% reduction in the diameter of the patch while maintaining UWB operation, as explained in Section III.

III. MEASURED AND SIMULATED RESULTS OF DESIGN I

Simulations have been performed using the commercial simulator HFSS which employs the finite element method [12]. Figure 3 shows the advantage of using a circular patch of sawtooth-like circumference of 18.2 mm diameter that was obtained using the superformula, as compared to a conventional circular patch antenna of optimal diameter of 25 mm [11], and a conventional circular patch antenna of 18.2 mm diameter. This figure shows that the proposed antenna yields better than 10 dB return loss across the entire FCC band. This was also achieved by the 25 mm diameter conventional circular patch antenna. The small size (18.2 mm) conventional circular patch antenna yielded smaller bandwidth whose lowest frequency is 3.6 GHz instead of 3.1 GHz. So, the use of sawtooth circular patch does increase the bandwidth if compared with conventional circular patch of the same diameter. The sawtooth-like circumference with its repetitive pattern behaves like a fractal geometry to increase the frequency bandwidth.

To verify that our proposed design of Fig. 1 operates as an UWB antenna over the FCC band (3.1-10.6 GHz), measured results for the return loss are obtained and compared with HFSS simulations, as shown in Fig. 4. Both measurements and simulations show a return loss that is better than 10 dB over the FCC band which proves the operation of our antenna as UWB antenna in this band. The difference between measurements and simulations may be due to the inaccuracies in measurements due to calibration errors and the reflections by the walls surrounding the measured antenna.

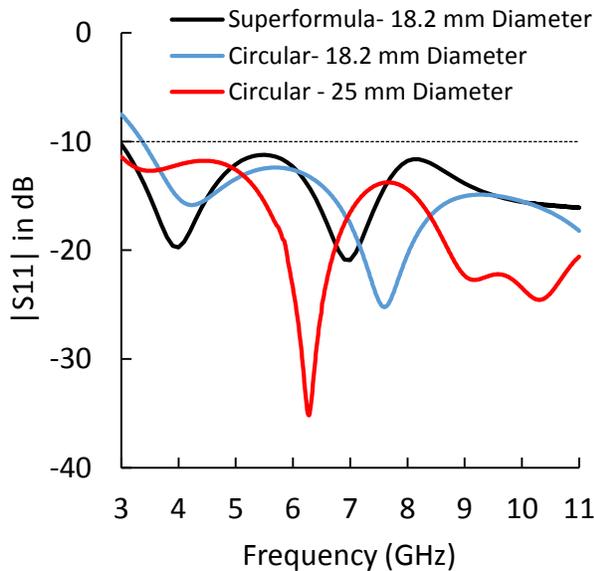


Fig. 3. Simulated $|S_{11}|$ versus frequency of Design I as compared to two UWB antennas with conventional circular patches having 25 mm and 18.2 mm diameters.

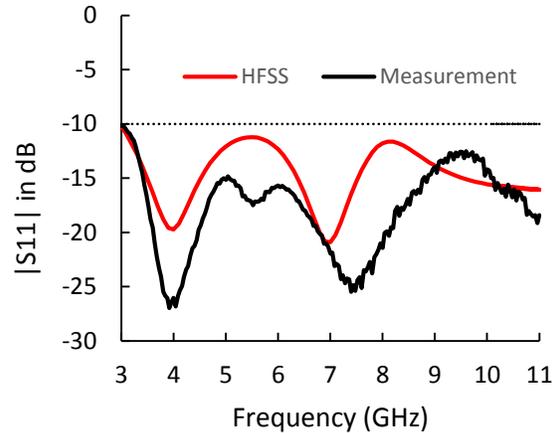


Fig. 4. Measured and simulated $|S_{11}|$ versus frequency for the proposed Design I.

Figure 5 shows measured and simulated results for the group delay of Design I over the FCC band. Both results show small variation of group delay response over the band which is less than 1.5 ns in the measurements and less than 0.5 ns in the simulations. The difference between the simulated and measured group delays is mainly because our antenna was not measured in an anechoic chamber so it suffered from the effect of reflections from the surroundings. This is contrary to the simulations where an absorbing boundary condition was assumed on the faces of the box surrounding the antenna. This is in addition to impedance mismatch at the connectors which can be reduced but not completely eliminated by calibration.

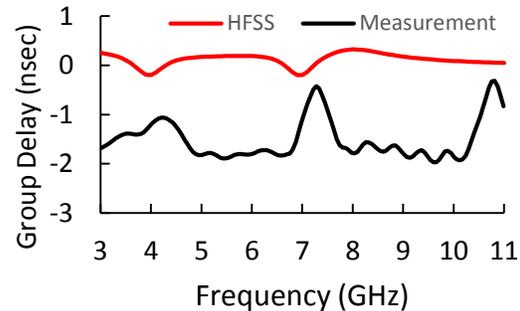


Fig. 5. Measured and simulated group delay for Design I.

The simulated radiation patterns of the proposed antenna (Design I) are shown in Figs. 6, 7, 8 in the E- and H- planes at 4 GHz, 7 GHz and 10 GHz, respectively, where the E-plane corresponds to the yz-plane and the H-plane corresponds to the xz-plane. These figures show that the proposed antenna is linearly polarized and exhibits nearly omnidirectional radiation pattern across the FCC frequency band. The pattern becomes less omni-

directional near the upper frequency range.

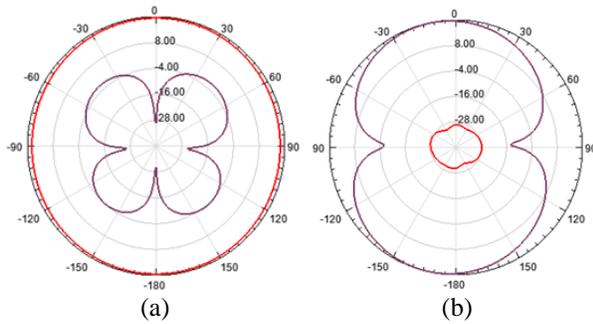


Fig. 6. Simulated radiation patterns for Design I at 4 GHz: (a) xz-plane (H-plane), and (b) yz-plane (E-plane). E_ϕ is shown in red color, and E_θ in black color.

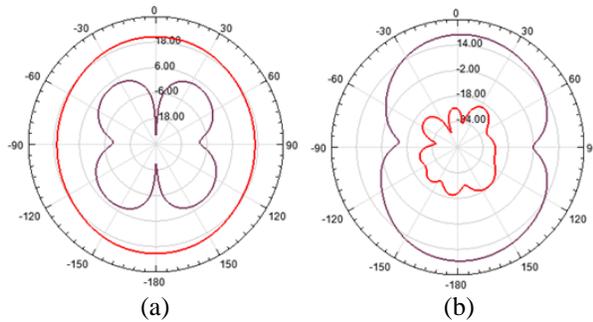


Fig. 7. Simulated radiation patterns for Design I at 7 GHz: (a) xz-plane (H-plane), and (b) yz-plane (E-plane). E_ϕ is shown in red color, and E_θ in black color.

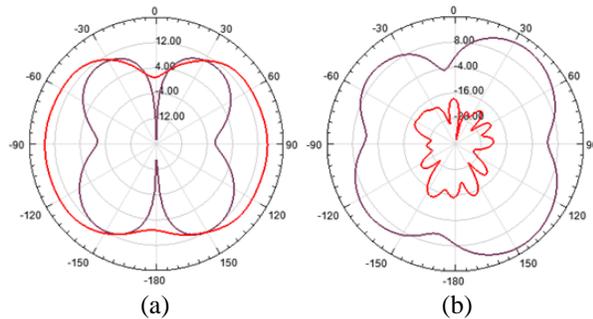


Fig. 8. Simulated radiation patterns for Design I at 10 GHz: (a) xz-plane (H-plane), and (b) yz-plane (E-plane). E_ϕ is shown in red color, and E_θ in black color.

Figure 9 shows the simulated peak gain of Design I as a function of frequency. The peak gain reaches a maximum of approximately 5 dBi and is almost stable above 4 GHz. The conventional circular patch of 18.2 diameter shows almost the same peak gain performance.

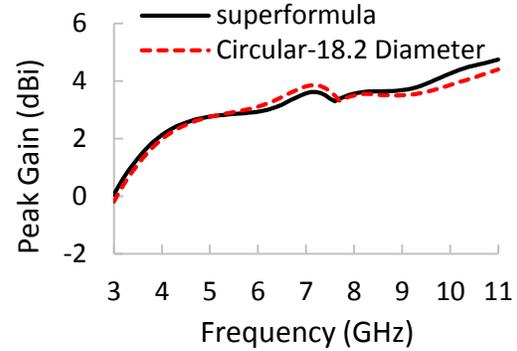


Fig. 9. Simulated peak gain versus frequency for Design I.

IV. MEASURED AND SIMULATED RESULTS OF DESIGN II

As explained in the introduction, Design I was modified to include two frequency notches that correspond to WiMAX (3.3-3.8 GHz) and WLAN (5-5.9 GHz). These notches were created using two arc-shaped slots etched on the sawtooth-like circular patch, as shown in Fig. 2. The arc with larger radius generates the WiMAX notch, while the arc with smaller radius generates the WLAN notch (see Fig. 2). Each arc length is about $\lambda/2$ at the corresponding notch band center frequency. An SRR was built on the bottom side of the substrate opposite to the patch. It is used to control the width of the WLAN frequency notch band and to increase the return loss at the WLAN notch.

To verify that our proposed design of Fig. 2 (Design II) operates as an UWB antenna over the FCC band (3.1-10.6 GHz) with two frequency notches corresponding to the WiMAX and WLAN bands, measured results were obtained for the return loss and compared with HFSS simulations, as shown in Fig. 10. Both measurements and simulations show a return loss that is better than 10 dB over the FCC band except at the notch locations where the return loss reaches 4 dB in measurements and 2 dB in the simulations.

Figure 11 shows measured and simulated results for the group delay of Design II over the FCC band. Both results show a small variation of group delay response over the band which is less than 3.5 ns in the measurements and less than 2 ns in the HFSS simulations. The differences between simulations and measurements may be due to calibration error and reflections from the setup surroundings.

The radiation patterns of the proposed antenna (Design II) are shown in Figs. 12, 13 and 14 in the E- and H- planes at 4 GHz, 7 GHz and 10 GHz, respectively. These figures show patterns that are very similar to those in Figs. 6, 7 and 8 for the case of no frequency notches.

So, the notching technique used in this paper does not cause any significant adverse effects on the radiation pattern. Figure 15 shows the simulated peak gain of Design II as a function of frequency. The peak gain reaches -2.5 dBi at the notch frequencies and has a maximum of about 1.5 dBi.

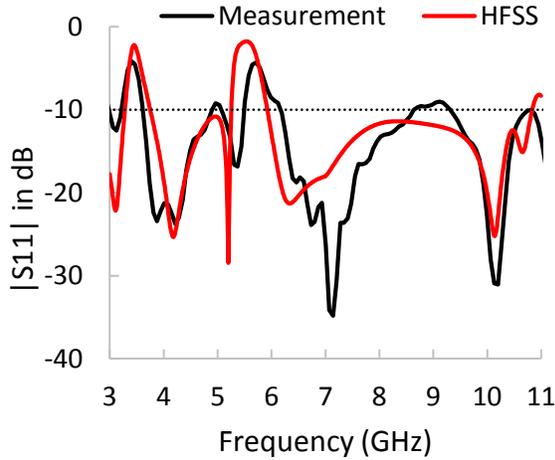


Fig. 10. Measured and simulated $|S_{11}|$ versus frequency for Design II.

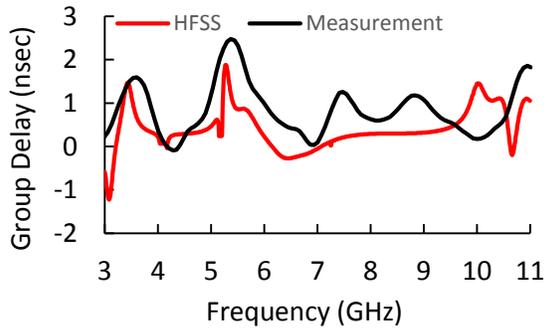


Fig. 11. Measured and simulated group delay for Design II.

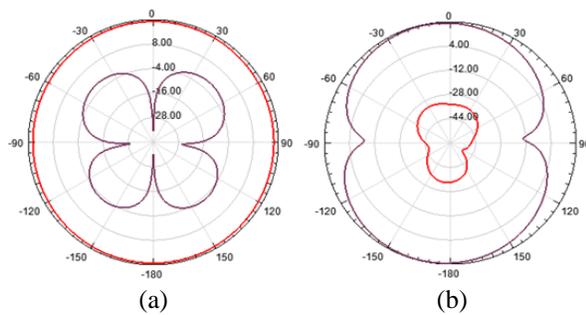


Fig. 12. Simulated radiation patterns for Design II at 4 GHz: (a) xz-plane (H-plane), and (b) yz-plane (E-plane). E_{ϕ} is shown in red color, and E_{θ} in black color.

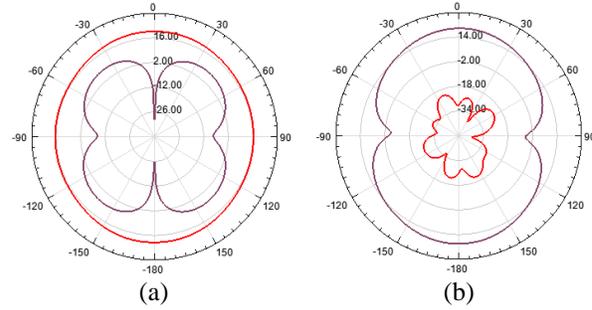


Fig. 13. Simulated radiation patterns for Design II at 7 GHz: (a) xz-plane (H-plane), and (b) yz-plane (E-plane). E_{ϕ} is shown in red color, and E_{θ} in black color.

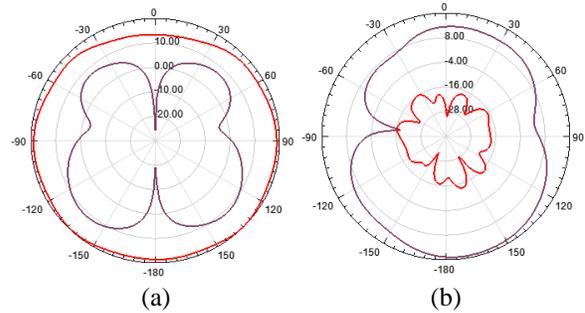


Fig. 14. Simulated radiation patterns for Design II at 10 GHz: (a) xz-plane (H-plane), and (b) yz-plane (E-plane). E_{ϕ} is shown in red color, and E_{θ} in black color.

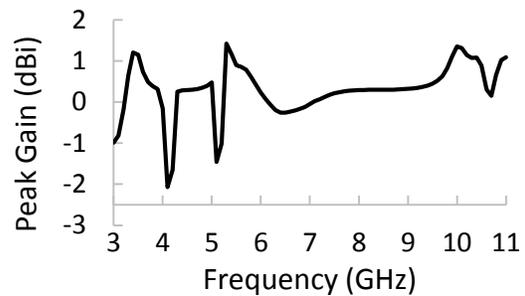


Fig. 15. Simulated peak gain versus frequency for Design II.

V. ANTENNA SIZE COMPARISON

In the designs presented in Figs. 1 and 2, we did not really optimize the size of the antenna which resulted in an antenna whose size is $L=40$ mm and $K=32$ mm. However, by simply reducing the feeding line and curved ground lengths ($V=3.32$ mm, $C=0.3$ mm) as well as reducing the lateral and longitudinal dimensions of the substrate ($L=24$ mm and $K=19$ mm), the final size of our antennas of Figs. 1 and 2 has been reduced to 24 mm \times 19 mm. Figure 16 illustrates the simulated and measured return loss of the two antennas of Figs. 1 and 2 for the reduced size. It is clear that the antennas still work well

in the UWB range (return loss better than 10 dB) and the second antenna has notch characteristics around 3.5 GHz and 5.5 GHz.

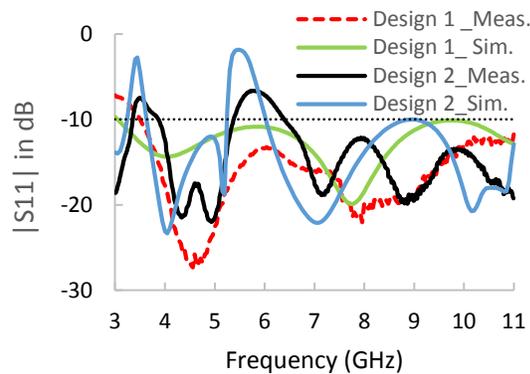


Fig. 16. The simulated and measured S_{11} (dB) for the reduced size antennas of Design I and Design II.

Table 1 shows a comparison between our reduced size designs and several other broadband antennas in terms of size. Our antenna is clearly comparable in size as compared to the other investigated antennas included in the table. In the table, the change in ϵ_r causes a change in the effective dielectric constant and characteristic impedance of the feed line. It also affects the input impedance of the antenna. This leads to a shift in the operating frequencies towards lower frequencies as ϵ_r is increased. The change in the impedance also affects the bandwidth of the antenna as the return loss at some frequencies may exceed 3 dB due to increased impedance mismatch leading to these frequencies becoming out of band.

Table 1: Size comparisons for different UWB antennas

Antenna	Our Reduced-Size Antenna	[10]	[11]	[13]	[15]	[18]
Band (GHz)	3-11	2.64-12	2.6-9.5	1.45-4.52	3.1-10.6	3.1-12.3
ϵ_r	3.85	3	2.33	4.4	9.5	4.4
Size (mm ²)	24 x 19	47 x 47	50 x 50	80 x 40	41.3 x 81.5	24 x 35
Antenna	[19]	[20]	[21]	[22]	[23]	[24]
Band (GHz)	2.7-9.3	2.6-10.8	2.2-17.5	2.615-14	2.69-12.53	2.9-15
ϵ_r	4.4	2.33	4.4	3.48	4.4	4.4
Size (mm ²)	40 x 50	50 x 50	20 x 24	25 x 37	12 x 18	25 x 38

VI. CONCLUSIONS

This paper proposes two new designs of compact UWB CPW-fed circular patch antennas with sawtooth-like circumference. The first antenna is a UWB antenna operating in the frequency range from 3.1-10.6 GHz. The second antenna has two frequency notches at the WiMAX and WLAN bands. The notches were generated using two

arc shaped slots and one SRR. The proposed antenna has smaller size as compared with several other antennas and can be easily designed and fabricated. As far as we know, the proposed design does not have any major shortcoming. However, the designer has to be careful so that the notch generated by the SRR and the notch generated by the smaller circular slot arc are aligned or slightly misaligned to control the frequency bandwidth at the WLAN notch. The differences between measurement and simulations in this paper may be due to calibration errors as well as reflections from the measurement setup walls.

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