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RESEARCH PAPER

Low-profile U-shaped DRA for ultra-wideband applications

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In this paper, a microstrip-fed U-shaped dielectric resonator antenna (DRA) is simulated, designed, and fabricated. This antenna, in its simple configuration, operates from 5.45 to 10.8 GHz. To enhance its impedance bandwidth, the ground plane is first modified, which leads to an extended bandwidth from 4 to 10.8 GHz. Then by inserting a rectangular metallic patch inside the U-shaped DRA, the bandwidth is increased more to achieve an operating band from 2.65 to 10.9 GHz. To validate these results, an experimental antenna prototype is fabricated and measured. The obtained measurement results show that the proposed antenna can provide an ultra-wide bandwidth and a symmetric bidirectional radiation patterns. With these features, the proposed antenna is suitable for ultra-wideband applications.

Keywords: Ultra-wideband applications, Dielectric resonator antenna, Low-profile antenna, Measurements

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I. INTRODUCTION

Responding to the growth demands for high data-rate communication systems, the Federal Communications Commission allocated the frequency band from 3.1 to 10.6 GHz for ultra-wideband (UWB) applications [1]. Since then, UWB systems have been attracted much academic and industrial research. UWB antennas, which play a key role in the UWB systems, occupy the most part of these investigations. To enhance the bandwidth of conventional antennas, many antenna designs have been proposed, such as coplanar waveguide (CPW)-fed slot antennas using a tuning stub with rectangular shape [2], circular shape [3], and fork-like shape [4] or CPW-fed planar broad-band monopole antennas (with rectangular, circular, semi-elliptical, and trapezoidal forms [5–8]). Almost, in all these antenna designs, the radiator element consists of metallic patch, which suffers from low radiation efficiency and high dissipation losses.

In the last two decades, the dielectric resonator antennas (DRAs) received special attention due to their features such as reduced size, high radiation efficiency, light weight, and absence of ohmic losses [9–11]. In the literature, several studies have been reported for wideband and UWB applications. First, for wideband applications various DRA designs have used different configurations, like using stacked segment dielectric resonators (DRs) [12], stacked-embedded DRs [13], hybrid DRA [14], and special geometries of DR, such as conical [15], tetrahedral [16], elliptical [17], stair [18], H-shaped [19], and P-shaped [20]. Second, for UWB applications some DRAs have been proposed using a half-cylindrical DRA [21], an A-shaped resonator [22], an inserted DRA excited by CPW [23], and a stacked rectangular DR antenna [24]. The U-shaped DRA can be considered as a bigger rectangular DR with small cut. Compared with the rectangular DR, the U-shaped DR can increase the resonances and impedance bandwidth, providing an impedance bandwidth between 60 and 80% [25, 26]. Compared to this design, the proposed U-shaped DRA provides a bandwidth that is larger than 120%, covering the entire operating UWB band.

In this paper, we propose a new low-profile U-shaped DRA fed by a microstrip line, covering the whole UWB spectrum and exhibiting a symmetric bidirectional radiation patterns with a cross-polarization level less than −20 dB, suitable for UWB applications. Moreover, the proposed antenna design provides an improved and stable gain compared with the existing UWB antennas. The electromagnetic analysis was carried out using both Computer Simulation Technology (CST) Microwave Studio based on finite integration technique in time domain and High Frequency Structure Simulator (HFSS) software, which utilizes finite-element method in frequency domain. The choice of two simulators, working in different domain and with different numerical methods, is done to check the obtained numerical results before approaching the fabrication of prototypes. Furthermore, to validate the proposed concept, an experimental antenna prototype was fabricated and measured. The measurements were performed using the Agilent 8722ES Network Analyzer. Section II describes the proposed antenna, and presents a parametric study. Then, the simulated and measured results are presented and discussed in Section III. Finally, a conclusion is drawn in Section IV.

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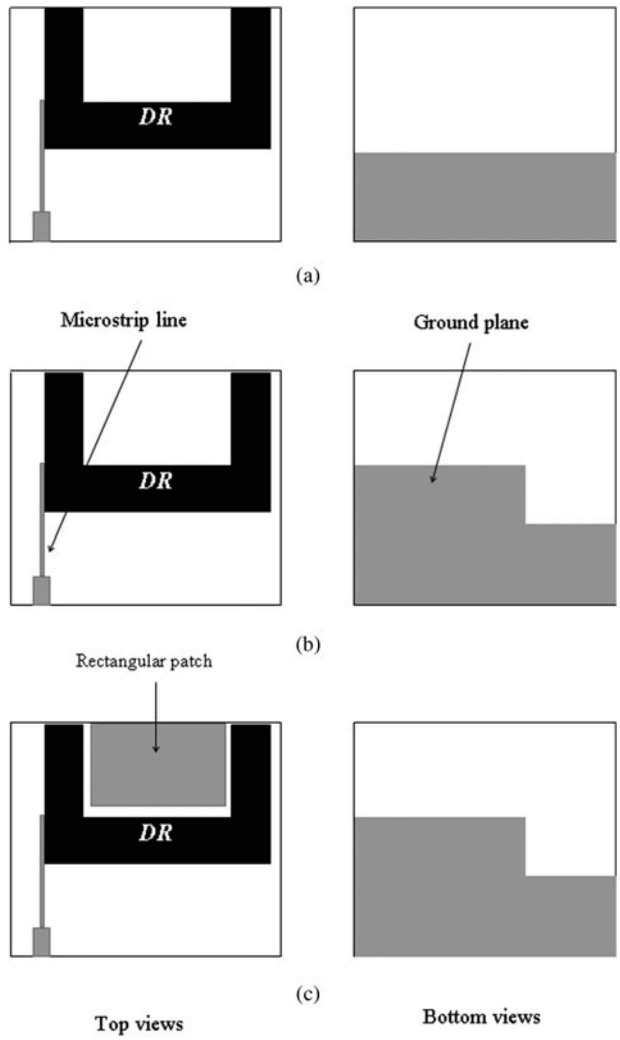

Fig. 1. Evolution of the proposed antenna: (a) antenna I, (b) antenna II, and (c) proposed antenna.

II. ANTENNA DESIGN AND OPTIMIZATION

A) Antenna's design evolution

The evolution of the proposed antenna is shown in Fig. 1. The simple configuration of this antenna consists of a U-shaped DR. This resonator is excited by a microstip-fed monopole located just beside its extremity and placed on a second substrate. This simple antenna configuration (Antenna I) provides an impedance bandwidth between 5.45 and 10.8 GHz (for $S_{11} < -10$ dB). The first step to enhance the impedance bandwidth consists of modifying the ground plane of the initial design antenna, as shown in Fig. 1(b) (Antenna II). The bandwidth is increased to cover from 4 to 10.8 GHz, as illustrated in Fig. 2. Then, a rectangular metallic patch is inserted inside the U shape of the DRA, as shown in Fig. 1(c).

Figure 2 shows the simulated results that were carried out by CST Microwave Studio. From these results, it can be seen that the bandwidth of the proposed antenna is improved compared with the first one, covering the entire UWB spectrum band.

The final configuration of the proposed design is illustrated in Fig. 3. It is composed of an U-shaped DR made of Rogers

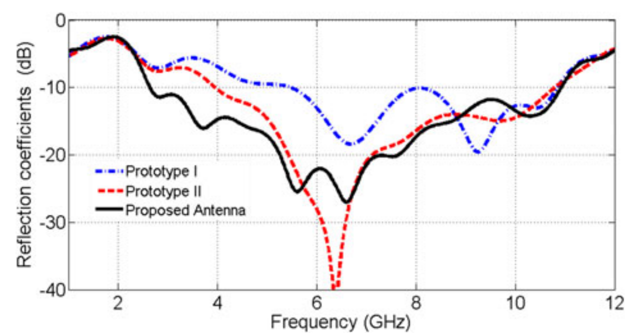

Fig. 2. Reflection coefficients for various antenna designs.

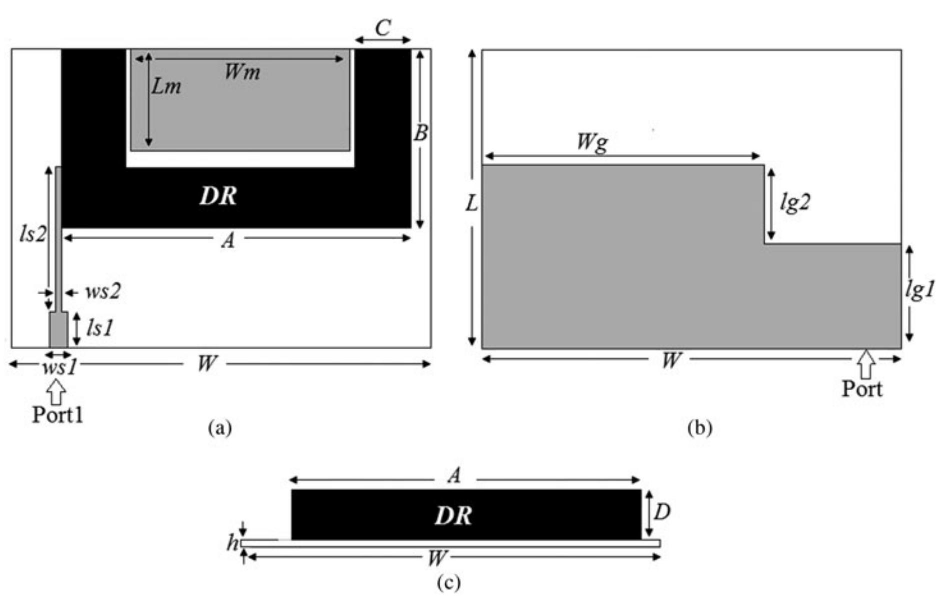

Fig. 3. Geometry of the proposed antenna: (a) top view, (b) bottom view, and (c) side view.

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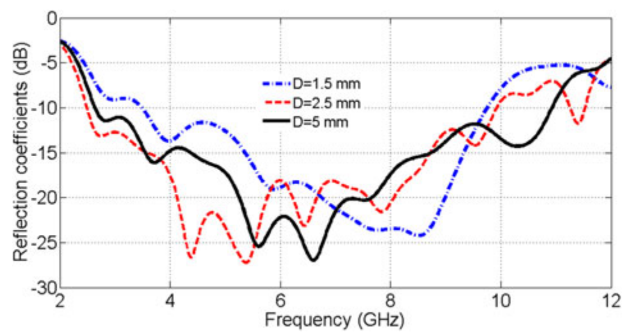

Fig. 4. Simulated reflection coefficient for different DR height '*D*' with $h = 0.762$ mm, $lg1 = 10.6$ mm, $lg2 = 8$ mm, and $Wg = 28.25$ mm.

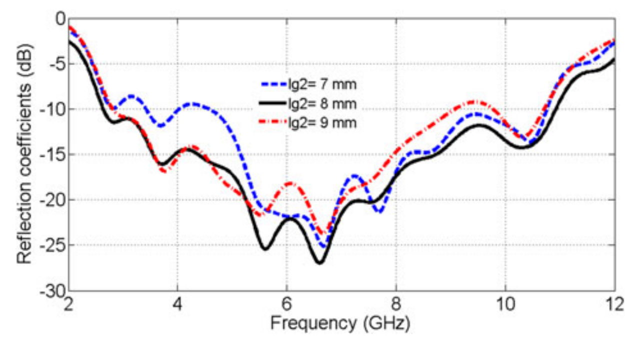

Fig. 8. Simulated reflection coefficient for different DR height '*lg2*' with $h = 0.762$ mm, $D = 5$ mm, $lg1 = 10.6$ mm, and $Wg = 28.25$ mm.

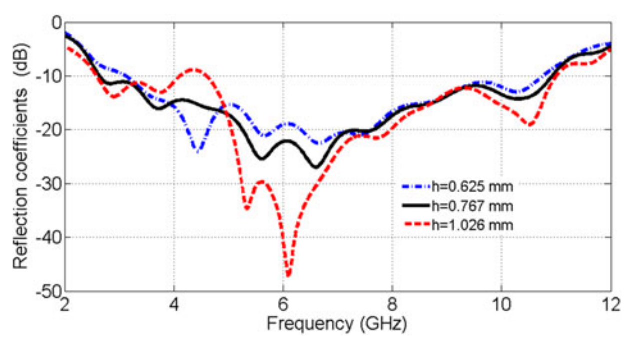

Fig. 5. Simulated reflection coefficient for different substrate thickness '*h*' with $D = 5$ mm, $lg1 = 10.6$ mm, $lg2 = 8$ mm, and $Wg = 28.25$ mm.

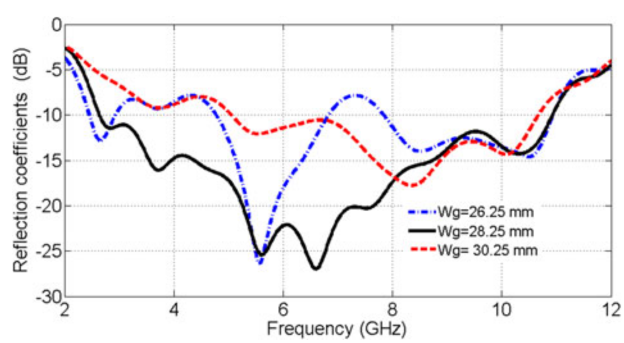

Fig. 6. Simulated reflection coefficient for different ground plane width '*Wg*' with $h = 0.762$ mm, $D = 5$ mm, $lg1 = 10.6$ mm, and $lg2 = 8$ mm.

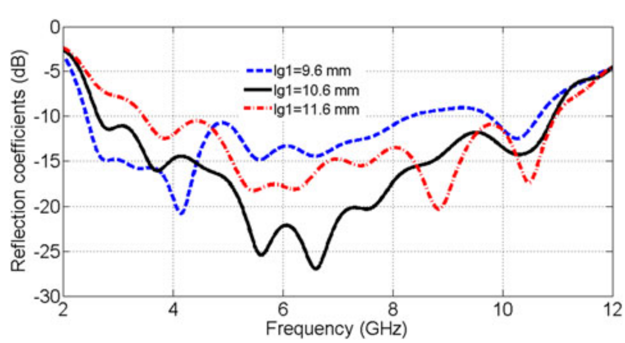

Fig. 7. Simulated reflection coefficient for different DR height '*lg1*' with $h = 0.762$ mm, $D = 5$ mm, $lg2 = 8$ mm, and $Wg = 28.25$ mm.

RT6010LM substrate with relative permittivity $\epsilon_r = 10.2$, loss tangent of 0.0023, and dimensions *A, B, C*, and *D*. The DR is mounted on Rogers RT588LZ substrate (with permittivity $\varepsilon_{rs} = 1.96$, loss tangent of 0.0019, and thickness *h*) with an area of $L \times W$. The excitation of the antenna was ensured by a 50 Ω transformer with width *ws1* and length *ls1*, and a microstrip line monopole of width *ws2* and length *ls1*. As illustrated in Fig. 3(b), the ground plane is partially printed below the substrate.

B) Parametric study

A parametric study was conducted to investigate the effects of key antenna parameters on the impedance matching.

This study was carried out by acting on the height of the DR *D*, the thickness of the substrate *h*, the width of the modified plane ground *Wg*, and the lengths of the ground plane *lg1* and *lg2*. The effect of the height of the U-shaped DR on the reflection coefficient (obtained from CST simulation) of the proposed antenna is shown in Fig. 4. It can be seen that the DR height *D* is a critical parameter on the antenna impedance bandwidth. By decreasing the parameter *D*, the impedance matching becomes poor at high frequencies and the bandwidth is reduced. The optimum value for this parameter is $D = 5$ mm. The reflection coefficient versus the frequency with different values of the substrate thickness was plotted in Fig. 5. From this figure, it can be concluded that the choice of the substrate thickness has an impact on the antenna performance in terms of the impedance bandwidth. The optimized thickness for maximum impedance bandwidth is 0.767 mm.

Table 1. The antenna bandwidth for different parameter values.

Antenna parameters		Bandwidth	
Designation	**Value in mm**	**GHz**	**%**
D	1.5	3.5–9.7	93.93
	2.5	2.48–9.92	120
	5	2.65–10.9	121.86
h	0.625	3.16–10.76	109.19
	0.767	2.65–10.9	121.86
	1.026	4.64–10.99	81.30
Wg	26.25	4.79–6.83	35.11
	28.25	2.65–10.9	121.86
	30.25	5.05–10.67	71.50
lg1	9.6	2.43–8.31	110.73
	10.6	2.65–10.9	121.86
	11.6	3.45–10.97	104.29
lg2	7	4.56–10.72	80.62
	8	2.65–10.9	121.86
	9	2.81–9.04	105.23

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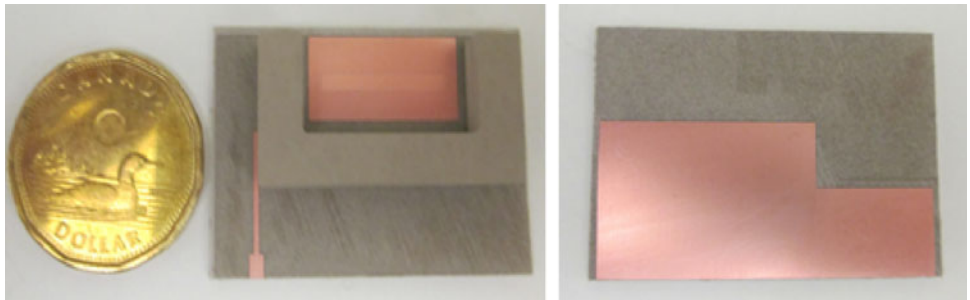

Fig. 9. The photograph of the final UWB antenna prototype: (a) top view and (b) bottom view.

Another parametric study was carried out on the modified ground plane width, as illustrated in Fig. 6. It is clearly observed from Fig. 6 that the decrease of the width Wg leads a narrow bandwidth. In addition, the impedance matching becomes poor at low frequencies when Wg is increased. The width of 28.25 mm is used as the optimized value.

Finally, the effect of the length of the ground plane ($lg1$ and $lg2$) is also studied, as illustrated in Figs 7 and 8. The lengths of the ground plane affect the reflection coefficient curve and decrease the antenna bandwidth. The optimum values for $lg1$ and $lg2$ are 10.6 and 8 mm, respectively.

Table 1 summarizes the calculated bandwidth obtained from these parametric studies. From the previous results, we can extract the optimized parameters of the proposed UWB antenna. Referring to Fig. 3, these optimized values are: $L =$ 30 mm, $W = 42$ mm, $h = 0.762$ mm, $A = 35$ mm, $B =$ 18 mm, $C = 6$ mm, $D = 5$ mm, $ls1 = 3.75$ mm, $ls2 = 14.5$ mm, $ws1 = 1.9$ mm, $ws2 = 0.7$ mm, $Lm = 10.3$ mm, $Wm = 22$ mm, $lg1 = 10.6$ mm, $lg2 = 8$ mm, and $Wg = 28.25$ mm.

III. MEASURED RESULTS AND DISCUSSION

An experimental prototype was fabricated and measured inside an anechoic chamber. Figure 9 shows a photograph of the fabricated antenna prototype.

The measured reflection coefficients along with the two simulated results (using CST and HFSS simulators) are plotted versus frequency, as shown in Fig. 10. From these graphs, it can be seen that the proposed antenna can provide an impedance bandwidth of 132% (NB: the bandwidth can be described in terms of percentage as BW% = 100%$(F_H - F_L)/F_C$, where F_H is the highest frequency in the band, F_L is the lowest frequency in the band, and F_C is the center frequency in the band), from 2.4 to 11.9 GHz, for return loss below −10 dB, largely covering the UWB spectrum band. The simulated results from HFSS and CST indicate that the bandwidth is between 115.4 and 121.8%, respectively. The phase of the reflection coefficient (S_{11}) is plotted versus the frequency in Fig. 11. From this curve, it can be seen that the phase seems to be linear through the entire operated frequency band.

The measured and simulated results show a reasonable agreement. However, the small discrepancy is mainly owed to fabrication tolerance, the misalignment of the DR when it is mounted on the substrate, and the radio-frequency cable of the network analyzer, which slightly affects the measurements of small antennas.

The radiation patterns in the E- and H-planes, at three different frequencies (3.5, 6.5, and 9.5 GHz), are plotted in Fig. 12 for both simulation and measurements. From the measured results, it can be observed that the proposed antenna provides a nearly omni-directional in the H-plane and bidirectional in the E-plane. Figure 13 shows the measured and simulated gain versus frequency. This UWB DRA exhibits gain that ranges from 2.5 to 6.2 dB through the operated frequency spectrum.

Table 2 reports the radiation efficiency of the proposed design at three selected frequencies. From these results, it can be shown that the U-shaped DR antenna provides high radiation efficiency with an average of 98.3%.

The fidelity factor (FF) is defined to estimate the quality of received signal waveform regarding the input signal. The FF can be calculated by using the following equation [27]:

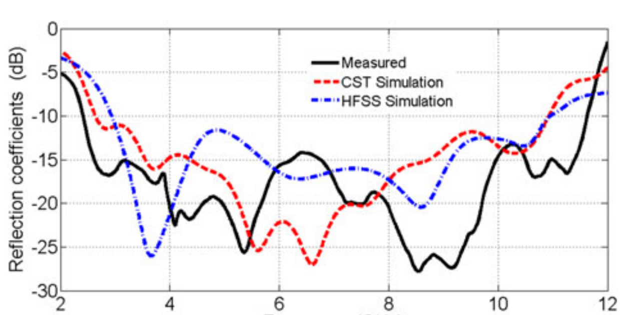

Fig. 10. Measured and simulated impedance matching bandwidth of the proposed antenna.

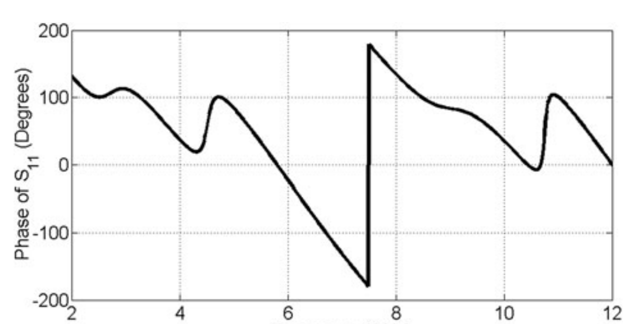

Fig. 11. The phase of S_{11} of the proposed antenna.

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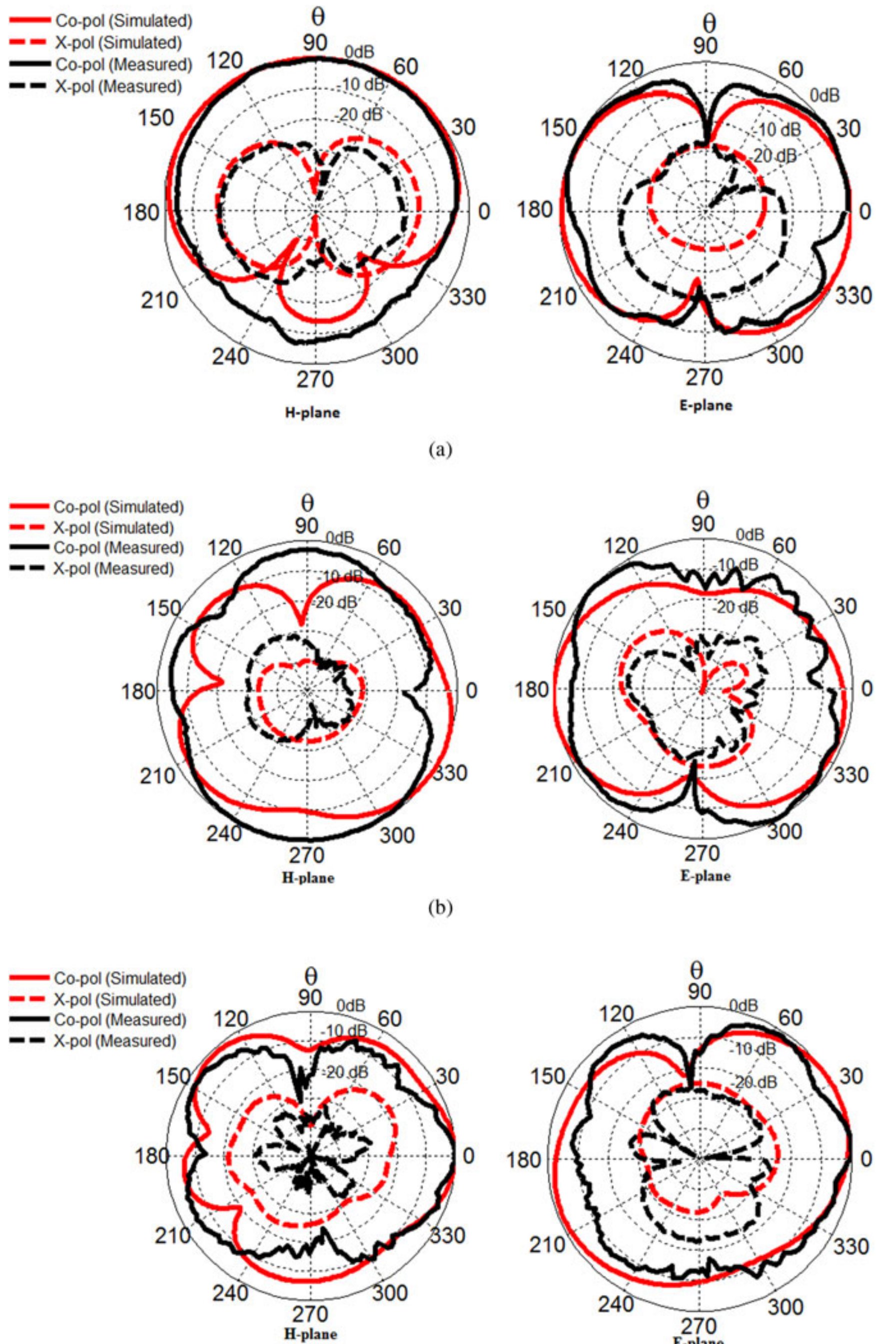

Fig. 12. Measured and simulated radiation patterns for the UWB antenna at: (a) 3.5 GHz, (b) 6.5 GHz, and (c) 9.5 GHz.

$$FF = \max\left[\frac{\int_{-\infty}^{+\infty} x_t(t)x_r(t+\tau)d\tau}{\sqrt{\int_{-\infty}^{+\infty}|x_t(t)|^2dt\int_{-\infty}^{+\infty}|x_r(t)|^2dt}}\right]. \qquad (1)$$

The FFs of the proposed structure are given in Table 3, for different orientations of the antennas. It is noticed that the FF varies by changing the antenna orientation, and its value ranges from 0.874 (for the side-by-side orientation) to 0.987 (for the back-to-back orientation).

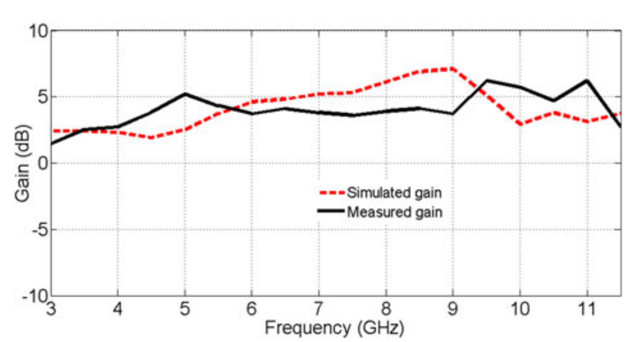

Fig. 13. Simulated and measured antenna gain.

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Table 2. Radiation efficiency of the antenna at selected frequencies.

Frequency (GHz)	Radiation efficiency, η (%)
3.5	97.4
6.5	98.2
9.5	99.3

Table 3. FF of the proposed antenna.

Antenna orientation	Fidelity factor
Face to face	0.973
Face to side	0.985
Side by side	0.874
Back to side	0.961
Back to face	0.954
Back to back	0.987

IV. CONCLUSION

In this work, a new low-profile DRA with U shape has been studied and proposed for UWB applications. The results obtained from the simulations and measurements have shown a good agreement in terms of bandwidth, radiation pattern, and gain. The measured results have shown that the proposed antenna covers the 2.4–11.6 GHz which covers the UWB spectrum (3.1–10.6 GHz), and provides a symmetric bidirectional radiation patterns. In addition, this UWB antenna has a stable gain in the whole operating frequency band. These attractive performances make the proposed design suitable for UWB systems.

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