Numerical Analysis and Design of a New Simple Compact Ultra-Wideband Dielectric Resonator Antenna with Enhanced Bandwidth and Improved Radiation Pattern

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Abstract **─** A new simple compact ultra-wideband (UWB) dielectric resonator antenna (DRA) is presented. The finite-difference time-domain (FDTD) method is used to the full-wave analysis of this structure. The antenna consists of a modified stepped microstrip fed monopole printed antenna loaded with a rectangular dielectric resonator, truncated ground plane and a parasitic strip underneath the dielectric resonator (DR). By using an optimized truncated ground plane and a combination of stepped feed line with dielectric resonator, an ultra-wide impedance bandwidth of 153% for ($S_{11} \leq$ -10 dB), covering the frequency range of (3.7–28 GHz) is achieved. The added parasitic strip can improve the radiation pattern, especially at high frequencies. The proposed antenna covers almost the entire UWB (3.1–10.6 GHz), Ku (12.4–18 GHz) and K (18–26.6 GHz) frequency bands. Also, this antenna has an omnidirectional and stable radiation pattern over the whole operating frequency range and a compact size of (15×20×5.8 mm^3) that make it suitable for wideband wireless system applications. This structure is light weight and can be easily fabricated. A prototype is built and measured. The simulated and measured results are in good agreement with the computed FDTD result.

Index Terms **─** Dielectric resonator antenna (DRA), finite difference time domain (FDTD), omnidirectional pattern, ultra-wideband (UWB) antenna.

I. INTRODUCTION

Recently, the demand for ultra-wideband (UWB) communication systems has rapidly increased due to their many advantages including the high data rate, high speed, low cost, high accuracy in localization systems or high resolution in radar applications. Hence, in most of the applications it is necessary that these systems have a wideband antenna with low profile, omnidirectional and stable radiation pattern, constant gain and constant group delay. The dielectric resonator antenna (DRA) has been recently proposed to be one of the attractive candidate antennas for UWB applications due to striking characteristics such as high radiation efficiency, light weight, small size, different feeding mechanisms, wide bandwidth, absence of ohmic losses and no excitation of surface waves. In the last two decades many techniques have been reported to broaden the impedance bandwidth of DRAs, such as stacked DRs [1-3], special feeding mechanisms [4,5] and conformal patch feeding [6,7]. Although these techniques have enhanced the DRA's bandwidth, however, most of these antennas have a large size and common deficiencies such as asymmetric and unstable radiation pattern and complicated structure.

In this article, a new compact ultra-wideband dielectric resonator antenna with enhanced bandwidth and improved radiation pattern is proposed. The proposed antenna covers uwb frequency band, and entire Ku and K-band (12.4–

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26.5 GHz). Lately, this frequency range receives some particular research interest due to the development of high frequency communication systems. By using the combination of a stepped monopole antenna with truncated ground plane and a rectangular dielectric resonator with proper position respect to the feeding structure, the considerable electromagnetic coupling between the feeding patch and DR can be obtained. As a result, the proposed DRA can provide an ultra-wide impendence bandwidth with symmetrical and stable radiation patterns. The rectangular dielectric resonator (RDR) is chosen because it provides some more advantages compared to cylindrical and hemispherical ones. The three dimensions of a RDR provide one degree of freedom more than cylindrical dielectric resonator, which can be used to control the impedance bandwidth of the antenna [8]. Moreover, a RDR gives more flexibility to the manufacturer making it more versatile in achieving a wide impedance bandwidth. In order to improve the radiation pattern at high frequencies, a parasitic strip underneath the DR is utilized. This strip eliminates some of the higher order modes that would cause a consistent omnidirectional pattern in H-plane across the whole operating frequency band (3.7–28 GHz). This DRA is simulated using a High Frequency Structure Simulator (HFSS) [9]. In addition to the Simulated and measured results, the FDTD calculated result is presented to validate the usefulness of the proposed antenna structure for UWB applications.

II. ANTENNA DESGIN

Figure 1 shows the configuration of the proposed antenna, which consists of a rectangular dielectric resonator and a stepped microstrip fed monopole antenna printed on an FR4 microwave substrate with size of 15×20 mm^2, thickness of 0.8 mm and dielectric constant of 4.4.

In theory, a DRA with a dielectric constant of one for the DR, would have the lowest Q-factor and therefore the widest bandwidth. In practice, however, there is a lower limit on the value of the dielectric constant required to contain the fields within the DRA in order to resonate. As a result, a relative permittivity around 10, which is normally used in related designs, is chosen for our DRA design [8]. The size of the DR has 7.5 mm length, 6 mm width, and 5 mm thickness, which is fabricated on Rogers RT/Duroid 6010 microwave dielectric material with a dielectric constant of 10.2. The feeding structure comprised of a 50 Ω microstrip transformer with W_f =1.6 mm width and L_f = 5.3 mm length and a stepped monopole antenna with lengths of L_1 = 4.3 mm, L_2 = 2.5 mm and widths of W_1 = 1 mm, W_2 = 4.3 mm. By applying this step-shaped feeding and adjusting its position underneath the DR (L_4), a significant coupling and a good impedance matching can be achieved. The truncated ground plane is printed on the bottom side of the substrate with size of 8.5×15 mm^2.

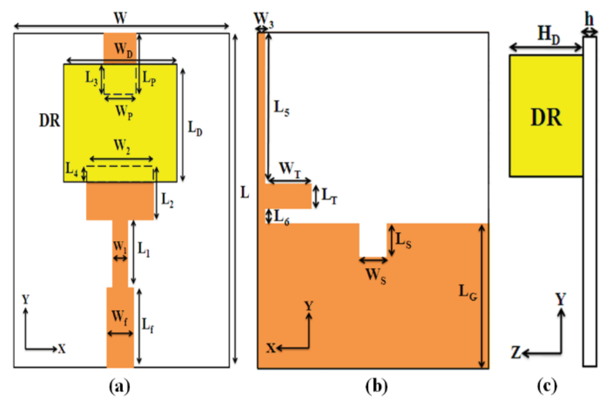

Fig. 1. Configuration of the proposed DRA: (a) top view, (b) bottom view, and (c) side view.

Figure 2 shows the design procedure of the proposed DRA. Also, the simulated reflection coefficients for the various antenna structures shown in Fig. 2, are compared in Fig. 3.

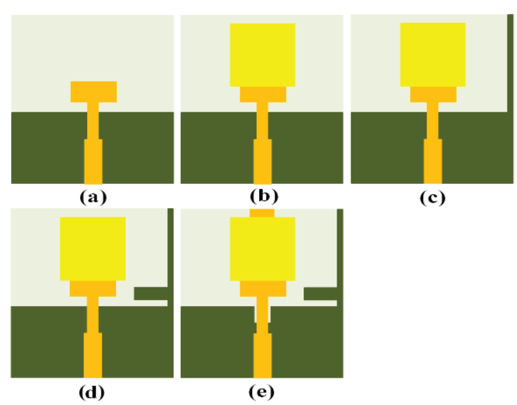

Fig. 2. Design procedure of the proposed DRA: (a) monopole antenna, (b) monopole antenna loaded with the DR, (c) monopole antenna loaded with the DR and the added tuning stub, (d) monopole antenna loaded with the DR and two added tuning stubs, and (e) proposed DRA.

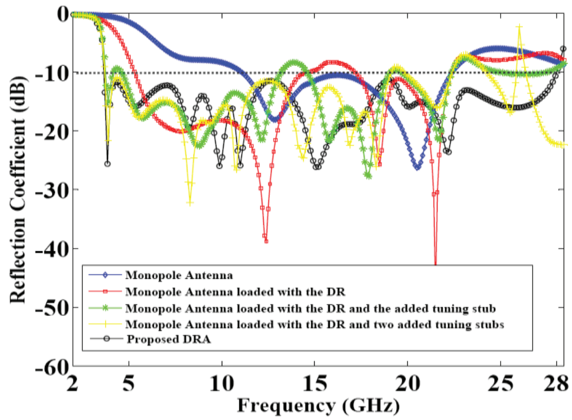

Fig. 3. Simulated reflection coefficients for the various antenna structures shown in Fig. 2.

The basic monopole antenna structure is shown in Fig. 2 (a). From Fig. 3, it can be seen that this monopole has two resonant frequencies and a wide impedance bandwidth from 11 to 22 GHz. In order to increase the bandwidth and shift the lower band towards lower frequencies, the DR is loaded on the monopole structure as shown in Fig. 2 (b). The initial dimensions of these structures are chosen in a manner that the resonant modes of the monopole and the DR can be excited with adjacent resonant frequencies to achieve a wideband operation. Since the DR is fed by a monopole structure in the xy-plane, the transverse electric modes $TE^{x}_{\delta mn}$, $(0 < \delta < 1)$ can be excited in it. By using the dielectric waveguide model (DWM) [10], the resonant frequencies of the DR can be given as follows:

$$f_0 = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{k_x^2 + k_y^2 + k_z^2} \ , \tag{1}$$

where

$$k_y = \frac{m\pi}{L_D} \ , \ k_Z = \frac{n\pi}{H_D} \ , \tag{2}$$

$$k_x^2 + k_y^2 + k_z^2 = \varepsilon_r k_0^2 \ , \tag{3}$$

$$k_x \tan(k_x W_D/2) = \sqrt{(\varepsilon_r - 1)k_0^2 - k_x^2} \ , \tag{4}$$

in which k_0 is free-space wavenumber, c is the speed of light in vacuum, and k_x, k_y and k_z are wavenumbers inside the DR in the three directions. The subscripts m, n denote the number of extremes in the y and z directions, respectively. However, since these resonant frequencies are determined for isolated DR and do not account for the coupling mechanisms between the DR and feeding structure, which may introduce new resonant frequencies, to further investigate the properties of DRA, simulations and optimization of the structures are performed using HFSS software. As illustrated in Fig. 3, the monopole antenna loaded with the DR achieves better impedance matching than the basic monopole antenna structure. However, there are some mismatches at the low frequency band (less than 5 GHz), the middle frequency band (around 16 GHz), and the high frequency band (more than 22 GHz). As shown in Fig. 2 (c), in order to obtain a better impedance matching at the low frequency band, a tuning stub is added to the truncated ground plane [11]. As it is observed from Fig. 3, although the added tuning stub can improve the impedance matching and reveal the resonant modes that occur due to the coupling effect between the DR and monopole structure, however, there is still a little mismatch at the low frequency band and the frequency band around 14 GHz. Therefore, to further improve these mismatches, another tuning stub is added to the modified truncated ground plane, as shown in Fig. 2 (d). It can be seen from Fig. 3 that, the monopole antenna loaded with the DR and two added tuning stubs can achieve better impedance matching than the previous structures, but there are still some mismatches at the high frequency bands. Thus, to improve these mismatches, a rectangular slot is etched on the modified truncated ground plane below the feed line, as illustrated in Fig. 2 (e). It is clearly observed from Fig. 3 that, the proposed DRA with the etched slot on the ground plane can achieve a wide impedance matching, even at the high frequency bands; because the rectangular slot creates a capacitive load that neutralizes the inductive nature of the feeding patch, especially at high frequency bands. It can be seen in Fig. 2 (e) that, a parasitic strip is added underneath the DR. This strip can eliminate some of the higher order modes and change the field distribution inside the DR, to achieve a stable omnidirectional radiation pattern in H-plane, especially at high frequency bands.

Design, simulation and optimization of the proposed DRA are carried out using HFSS, leading to the following optimal dimensions: L = 20 mm, W = 15 mm, L_f = 5.3 mm, W_f = 1.6 mm, L_1 = 4.3 mm, W_1 = 1 mm, L_2 = 2.5 mm, L_D = 7.5 mm, W_D = 6 mm, H_D = 5 mm, L_P = 3 mm, W_P = 2 mm, L_3 = 2 mm, L_4 = 0.6 mm, L_T = 1.5 mm, W_T = 3 mm, L_S = 1.9 mm, W_S = 1.4 mm, L_G = 8.5 mm, W_3 = 0.5 mm and h =

0.8 mm.

In order to further investigate the characteristics of the proposed DRA and achieve the optimum antenna performance, a parametric study was carried out. The Ansoft HFSS software, which is based on the finite element method, is used for the parametric analysis of reflection coefficient. The key parameters of the proposed antenna are studied by changing one parameter at a time and fixing the others.

Figure 4 shows the effect of the truncated ground plane length (L_G) on the reflection coefficient of the proposed DRA. It can be seen that the best matching and impedance bandwidth is achieved at $L_G = 8.5$ mm.

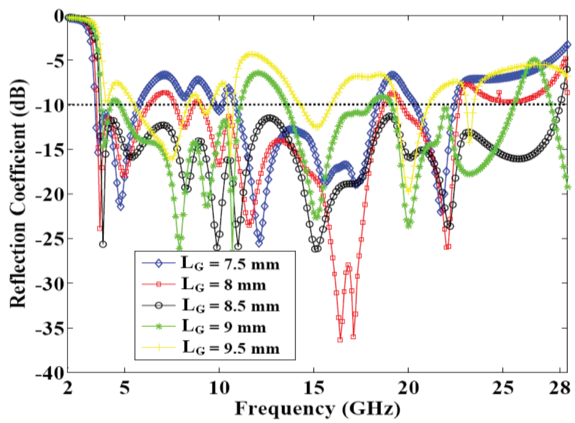

Fig. 4. Simulated reflection coefficient for various length of L_G.

The effect of the first tuning stub length (L_5) is shown in Fig. 5. It is observed that the impedance matching is degraded by increasing the length of L_5, at the low frequency band. Therefore, the optimized value of L_5 is equal to 9 mm. Another parametric study is done on various values of L_6, which it indicate the distance between the second tuning stub and the truncated ground plane, as shown in Fig. 6. It is observed that the impedance matching is degraded by increasing the length of L_6, at the low frequency band. So the best impedance matching is achieved at $L_6 = 1$ mm. Figure 7 shows the effect of the W_2 parameter. It can be seen that for the lower value of W_2, the impedance matching is poor, because of the weak coupling between the feeding structure and the DR. On the other hand, for the higher value, there are some mismatches. Therefore, the best impedance matching is achieved at $W_2 = 4.3$ mm.

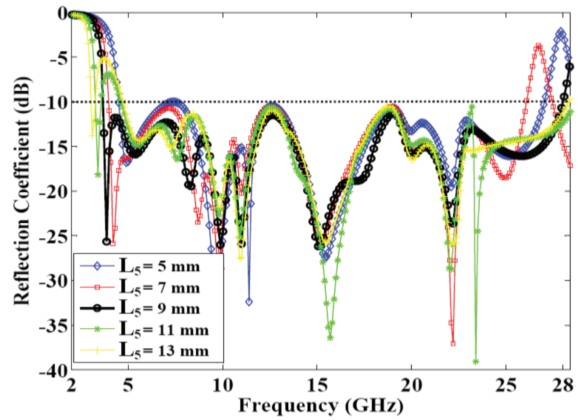

Fig. 5. Simulated reflection coefficient for various length of L_5.

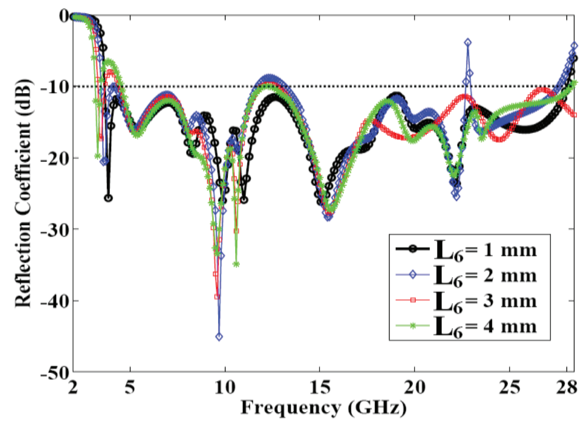

Fig. 6. Simulated reflection coefficient for various length of L_6.

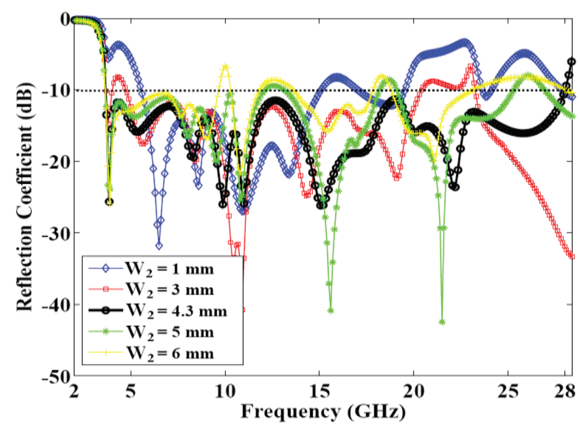

Fig. 7. Simulated reflection coefficient for various length of W_2.

III. FDTD ANALYSIS

FDTD methods are widely used to characterize and simulate electromagnetic wave propagation and antenna structures [12]. In this work, the FDTD algorithm with uniform Cartesian grid is applied to analyze the proposed DRA [13,14]. The space steps used in the FDTD analysis are Δx, Δy, and Δz. All of them should be smaller than $\lambda_{min}/20$, where λ_{min} is the minimum operating wavelength of the antenna structure. In order to correctly model the dimensions of the antenna, the space steps have been chosen so that an integral number of nodes will exactly fit the rectangular dielectric resonator. Unfortunately, this means the stepped monopole structure lengths, widths, and placement will be offset by a fraction of the space step. The sizes of the space steps are carefully chosen to minimize the effect of this error. To model the thickness of the substrate (h) correctly, Δz is chosen so that four nodes exactly match the thickness. An additional 14 nodes in the *z* and *-z* directions are used to model the free-space above the DR and under the substrate, respectively. The space steps used are $\Delta x = 0.2$ mm, $\Delta y = 0.395$, and $\Delta z = 0.2$ mm.

As in [14], Mur's first order absorbing boundary conditions (ABC) are used to terminate the computational domain. Hence, the tangential electric filed components on the six outer boundaries will obey the one-dimensional wave equation in the direction normal to the mesh wall. Since the reflections from the antenna structure will be reflected again by the source wall, to eliminate this, the microstrip line feeding structure is extended with additional 30 nodes in the *-y* direction, and in order to reduce the source distortion, a changeable source plane is assumed following Sheen, et al. [14]. This plane is a magnetic wall all over the source plane and when the excitation pulse has been fully launched, it is substituted by Mur's first order ABC. Thus, the length of the microstrip line from the source plane to the reference plane is $30\Delta y$. The total size of the computational domain is $76\Delta x \times 81\Delta y \times 57\Delta z$.

A simple voltage source approximation is used to model the feed of the microstrip line. A baseband Gaussian pulse of half-width $T = 10$ ps is applied at the source plane to suit the frequency range of interest (0–30 GHz). The time delay t_0 is set to be $3T$ so the Gaussian will start at approximately 0. The time step used, according to the Courant stability condition [12], is $\Delta t = 0.2$ ps. The iterations are performed for 8000 time steps to allow the input response to vanish.

IV. RESULTS AND DISCUSSION

To validate the proposed design, an optimized DRA was fabricated and measured, which is shown in Fig. 8. The optimized DRA parameters are as follows: L = 20 mm, W = 15 mm, $L_f = 5.3$ mm, $W_f = 1.6$ mm, $L_1 = 4.3$ mm, $W_1 = 1$ mm, $L_2 = 2.5$ mm, $W_2 = 4.3$ mm, $L_D = 7.5$ mm, $W_D = 6$ mm, $H_D = 5$ mm, $L_P = 3$ mm, $W_P = 2$ mm, $L_3 = 2$ mm, $L_4 = 0.6$ mm, $L_T = 1.5$ mm, $W_T = 3$ mm, $L_S = 1.9$ mm, $W_S = 1.4$ mm, $L_G = 8.5$ mm, $L_5 = 9$ mm, $W_3 = 0.5$ mm, $L_6 = 1$ mm and h = 0.8 mm. The impedance bandwidth was measured by using an Agilent 8722ES vector network analyzer. In addition to the measured and simulated reflection coefficients of the proposed antenna, Fig. 9 shows the calculated result by the FDTD method. A good agreement between the results is observed.

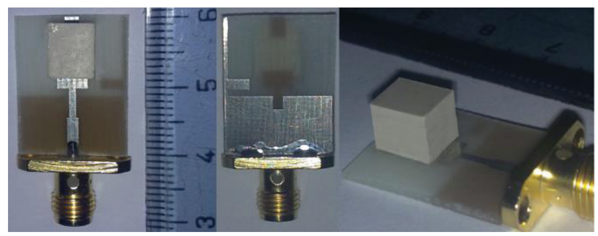

Fig. 8. Photograph of the fabricated DRA.

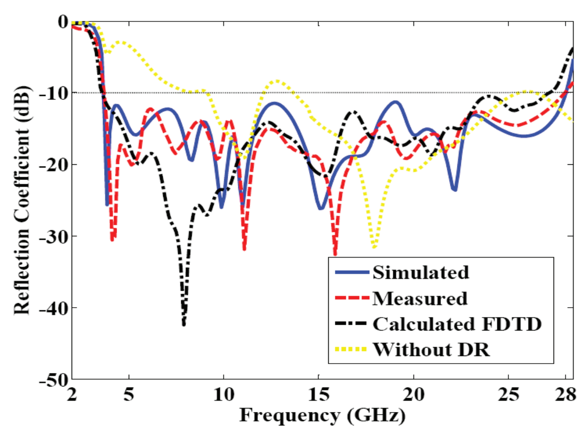

Fig. 9. Reflection coefficients of the proposed DRA.

The measured impedance bandwidth covers the frequency range (3.7–28 GHz), which is equivalent to 153% for ($S_{11} \leq -10$ dB). The discrepancy between the simulated and measured results can be due to the tolerance in manufacturing, imperfect soldering effect of the SMA connector, and also the accuracy of the simulation due to the wide range of simulation frequencies. The errors in the FDTD calculated result may be due to the modeling error that occurs primarily in the inability to match all of the circuit dimensions, and the imperfect absorbing condition of outer boundaries. Moreover, the simulated reflection coefficient of the proposed antenna without the dielectric resonator is also shown in Fig. 9. It is observed from these results, when the antenna is with the DR a better impedance matching due to the loading effect, with some excited resonant modes in the DR can be achieved. As a result, an ultra-wide bandwidth is obtained by using a dielectric resonator.

The proposed DRA is also measured in far field anechoic chamber. Figure 10 shows the measured and simulated radiation patterns in the H (xz)-plane and E (yz)-plane at five different frequencies (4, 8, 11, 16 and 22 GHz). In the H-plane, it can be seen that the radiation patterns are almost symmetrical and stably omnidirectional across the operating frequency range. However, the radiation patterns in the E-plane are not as symmetrical as in the H-plane and have some deformations at higher frequencies due to the effects of higher order modes.

Figure 11 plots the measured and simulated peak gain of the proposed antenna. It is seen that the peak gain is almost stable in the entire operating frequency range, and slightly increases with frequency due to the higher order modes excitation. The estimated radiation efficiency of the proposed antenna is more than 90% across the operating frequency range.

Group delay is an important parameter in UWB antenna design because it represents the degree of distortion of the transmitted pulses in the UWB communication. The group delay should be almost constant for a good pulse transmission. The measured and simulated group delay of the proposed antenna is shown in Fig. 12. As it can be seen, the group delay variation is less than 2 ns in the whole frequency band. This confirms that the proposed DRA is suitable for UWB communication.

As mentioned in the introduction section, different shapes of DRAs are investigated for wideband application. To determine the validity of the proposed UWB DRA, a comparison with the some existing designs in the literature is presented in Table 1. The comparison shows that the proposed antenna achieves wider bandwidth and smaller volume than other DRAs.

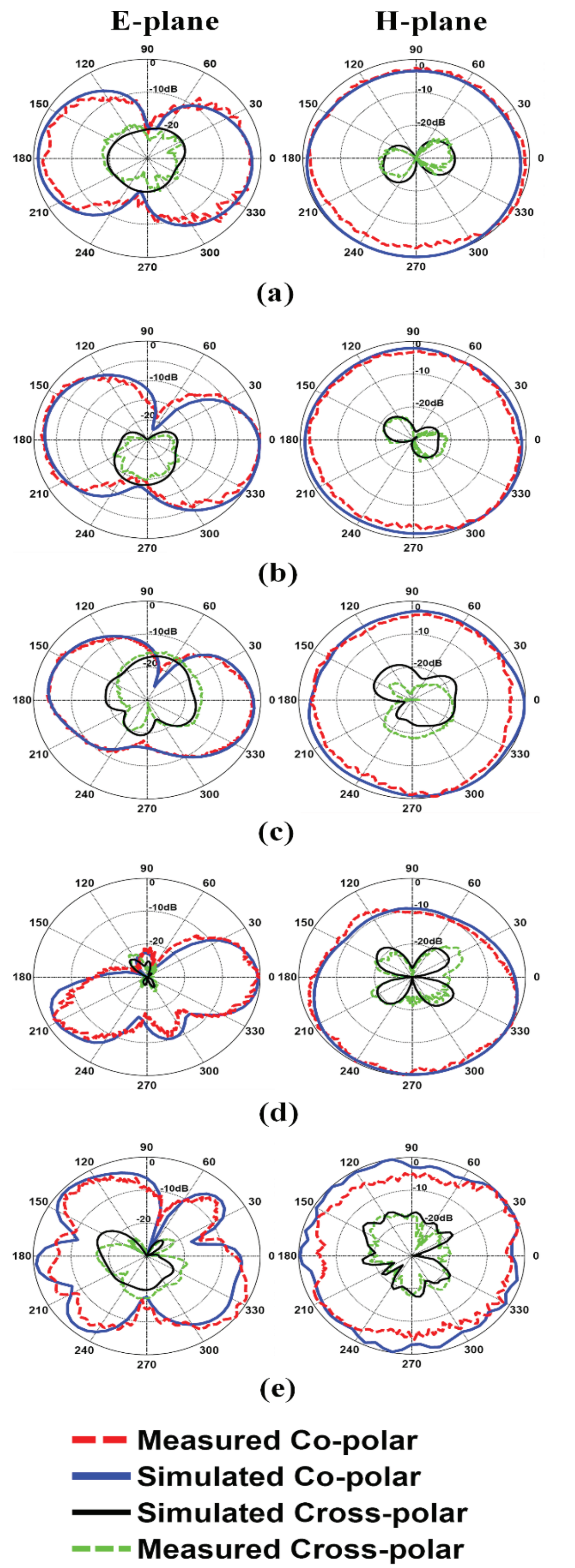

Fig. 10. Measured and simulated radiation patterns at frequencies: (a) 4, (b) 8, (c) 11, (d) 16, and (e) 22 GHz.

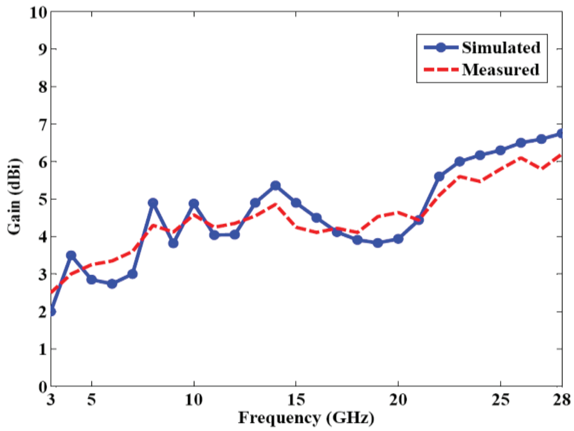

Fig. 11. Measured and simulated peak gain of the proposed DRA.

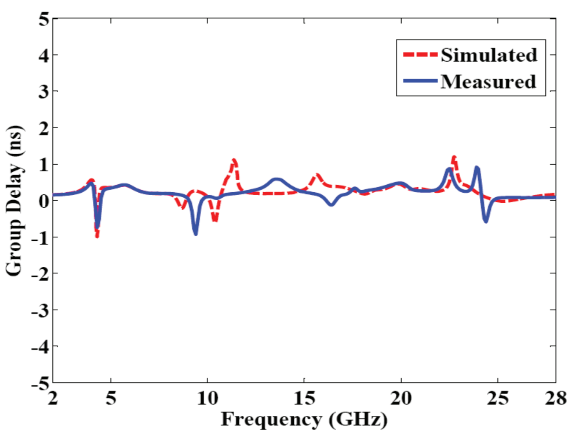

Fig. 12. Measured and simulated group delay of the proposed DRA.

Table 1: Comparison between the proposed antenna and other designs

Parameters	Volume (mm3)	Height (mm)	Bandwidth	Gain (dBi)
L-shaped DRA [3]	44732	24	1.71-2.51 GHz (80%)	6.1-8.7
Hybrid DRA [5]	15280	7.64	3.1-10.6 GHz (109.5%)	2-5
U-shaped DRA [6]	61572	20.5	3.115-7.635 GHz (84.09%)	3-8.5
Asymmetrical T-shaped DRA [7]	48240	13.4	3.81-8.39 GHz (75%)	3.24-7.35
Proposed antenna	1740	5.8	3.7-28 GHz (153%)	2.5-6.75

V. CONCLUSION

A new simple compact UWB dielectric resonator antenna with enhanced bandwidth and improved radiation pattern has been proposed. The uniform grid FDTD method has been used to analyze the scattering characteristic of the proposed DRA. By using a stepped monopole antenna loaded with a rectangular dielectric resonator and an optimized truncated ground plane, an ultra-wideband DRA with increased bandwidth is achieved and the parasitic strip is added underneath the DR to improve the radiation pattern at high frequencies. The measured results demonstrate that the proposed DRA achieves an ultra-wide impedance bandwidth about 153%, covering the frequency range of (3.7–28 GHz). Also, this antenna provides almost stable omnidirectional radiation patterns, stable gain and nearly constant group delay over the entire operating frequency range. In addition to the above characteristics, this DRA has a simple structure, compact size and easy fabrication that make it a good candidate for UWB applications and systems.

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