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Design and Development of a Wideband Fractal Tetrahedron Dielectric Resonator Antenna with Triangular Slots

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Abstract—In this paper, a fractal tetrahedron shaped dielectric resonator antenna (DRA) design for wideband applications is proposed. Two triangular-shaped fractal slots of different sizes are introduced to reduce Q-factor of DRA and in turn to achieve wide bandwidth (BW). Internal coaxial feeding is utilized for good impedance matching and ease of fabrication. The proposed fractal DRA is fabricated and tested. The measured results are in good agreement with the simulated ones. Measured impedance bandwidth of about 72.3% covering frequency band of 3.8–8.1 GHz is achieved. Good separation between co- and cross-polarized radiation patterns in the broadside direction is achieved. Various design parameters and associated results are discussed in this paper.

1. INTRODUCTION

Nowadays, dielectric resonator antennas (DRAs) are preferred over microstrip patch antennas by researchers worldwide due to their several advantages. The DRAs provide advantages such as wide bandwidth, low conduction losses, good mechanical strength, high radiation efficiency and no surface waves [1–3]. Additionally, various feeding techniques can be easily incorporated.

The bandwidth of a DRA is inversely proportional to the square root of the permittivity of the material. Also, the size of a DRA is inversely proportional to the square root of the permittivity [4]. Thus, it is clear that the bandwidth of a DRA is directly proportional to the size of the DRA. So, wideband DRAs can be designed, but its compactness cannot be maintained. This drawback of DRA can be overcome by using fractal geometry on the DRA structures.

Fractal geometry helps in designing compact antennas while improving overall bandwidth of the antenna. It also helps in reducing mutual coupling when being used in an array system [5]. Many researchers have proposed the use of various fractal geometries for DRA designs to achieve wide bandwidth. Altaf et al. in [6] have proposed circularly polarized spidron-shaped fractal DRA to achieve about 37.29% bandwidth. Dhar et al. in [7] have proposed Minkowski fractal DRA design and achieved wide bandwidth of about 64%. Pattnaik et al. in [8] have proposed Sierpinski carpet based stacked DRA design and achieved 25.52% bandwidth for X-band applications. Sankaranarayanan et al. in [9] have used fractal Koch snowflake geometry on cylindrical shaped dielectric resonator antenna to achieve around 56.5% bandwidth. Liu et al. in [10] have used a triangular shaped Sierpinski fractal geometry on tetrahedron DRA to achieve dual-band operation covering wireless local area network (WLAN) as well as worldwide interoperability for microwave access (WiMAX) bands with 14.46% and 27.78% bandwidth, respectively. The authors of this paper have proposed prism shaped DRA designs with Sierpinski carpet fractal geometry [11] and achieved 57.5% bandwidth, covering the entire X-band. A fractal rectangular curve (FRC-1) shaped DRA is proposed in [12], where 5% improvement in bandwidth and 0.25 dB improvement in gain are achieved. Azari et al. in [13] have introduced a Koch fractal based

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wire antenna inside the two conical-shaped DRAs. This monopole DRA design covers a frequency band of 2–40 GHz considering −8 dB as reference for measuring impedance bandwidth. Haji-Hashemi et al. in [14] have incorporated a Koch fractal geometry on a dual-band conical-shaped DRA. About 9% and 4% improvement in bandwidth for both the bands is achieved in comparison to a simple conical DRA.

The researchers have considered variety of geometries for the DRA design. However, a triangular geometry requires less space than other geometries [15] and has been used by many designers. For example, Lo et al. in [15] have achieved around 3% impedance bandwidth using a very compact, high permittivity equilateral triangular DRA design. Kumari et al. in [16] have used the concept of stacking three differently sized equilateral triangular DRAs on top of each other to achieve wide bandwidth of about 41% (4 to 6.02 GHz). Maity and Gupta in [17] have proposed a design of isosceles triangular DRA placed on a ground plane and excited using coaxial probe. They have claimed 47.4% bandwidth covering 4.33–7.02 GHz band.

In this paper, the authors introduce two fractal triangular slots in a tetrahedron-shaped DRA and achieve encouraging results. The proposed fractal design is not complex and can be easily fabricated in comparison to other fractal geometries. Also, the design is mechanically stable and can be incorporated in any position. The fractal triangular slots help in reducing the Q-factor and in turn wider bandwidth. The measured impedance bandwidth of 72.3% covering frequency range from 3.8–8.1 GHz is achieved, which is 1.5 times higher than the bandwidth reported in [17].

The proposed DRA geometry and its design parameters are discussed in Section 2. Section 3 covers the discussion on parametric study and various simulated and measured results. Finally, the conclusions are drawn in Section 4.

2. ANTENNA GEOMETRY AND DESIGN

Figure 1 shows the geometry of a fractal tetrahedron DRA. The proposed DRA of height $h = 19$ mm is placed on a square ground plane having side length $L = 140$ mm. The DRA is designed using Rogers RO 3010 material having permittivity $\varepsilon_r = 10.2$. Coaxial probe feeding is used to excite the DRA. Rigorous parametric analysis is carried out using FEM based simulation tool (HFSS) to achieve optimized DRA dimensions. The optimized dimensions are as follows: $L = 140$ mm, $c = 10.18$ mm, $a = b = 19.6$ mm, $c_1 = 3$ mm, $h_1 = 3.8$ mm, $c_2 = 2$ mm, and $h_2 = 3.8$ mm.

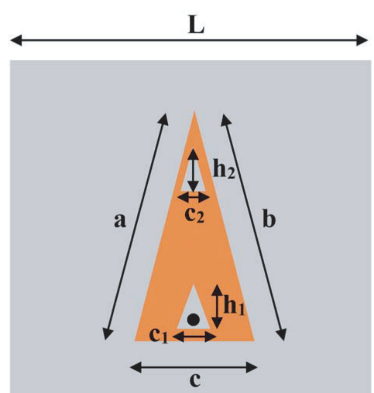

Figure 1. Geometry of a fractal tetrahedron DRA.

The coaxial probe is placed inside the triangular slot for better impedance matching. The height of the probe is also adjusted so as to achieve wider bandwidth.

3. PARAMETRIC STUDY AND ASSOCIATED RESULTS

Figure 2 shows the iterative transition from simple tetrahedron DRA in [17] to the proposed fractal tetrahedron DRA design. Internal coaxial feeding is used from first iteration onwards as it provides

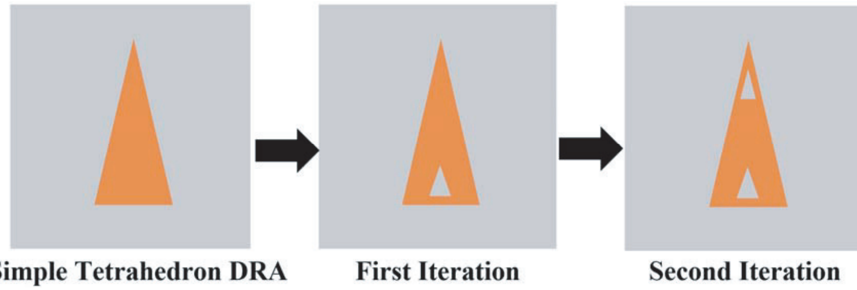

Figure 2. Iterative transition from simple tetrahedron DRA to proposed DRA design.

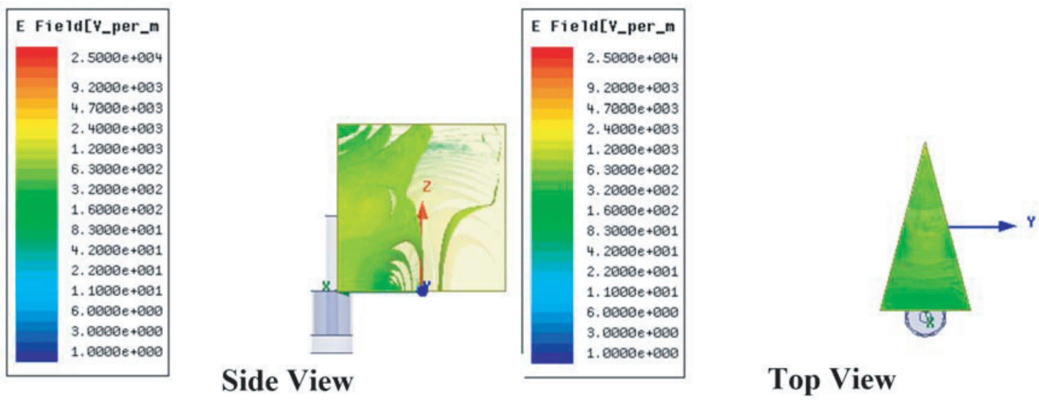

Figure 3. Internal electric field distribution in simple tetrahedron DRA at 4 GHz.

better impedance matching than outer coaxial feeding. In the first fractal iteration shown in Fig. 2, a triangular slot near the base of tetrahedron DRA is introduced. This lower triangular slot helps in improving the impedance bandwidth from 47.4% to 66.2%. Fig. 3 shows the internal electric field distribution of a simple tetrahedron DRA from side and top views at 4 GHz. From the side view, it can be observed that maximum electric field is concentrated near the base of a tetrahedron DRA while there is minimal field distribution near the apex. So, a triangular slot near the base helps in improving the return-loss performance around 4 GHz. Also, based on the results of eigen mode solver of HFSS, it is found that multiple resonances are created near 4 GHz by introducing a fractal triangular slot near the base. Such multiple nearby resonances get transformed into a broadband characteristic. As a result, bandwidth improvement is observed near lower frequency band.

The size of a lower triangular slot is optimized by scaling down its base with reference to a simple tetrahedron DRA base. Fig. 4 shows the return-loss performance of the first iteration DRA design for different scaling values. It is clear that as the scale value (c_1/c) is reduced from 0.9 to 0.3, the impedance bandwidth improves from 54.2% to 66.2%. To further improve the impedance bandwidth, the second fractal triangular slot is introduced near the apex of a tetrahedron. By introducing a second fractal slot, simulated impedance bandwidth improvement from 66.2% to 77.6% is achieved. The position of an upper triangular slot is decided based on the internal electric field distribution in the first iteration DRA design. Fig. 5 shows the internal electric field distribution in the first iteration DRA design at 8 GHz. It is clear that apex portion of the first iteration tetrahedron has strong electric field distribution apart from the base region. So, upper triangular slot at the position of strong field distribution helps in improving simulated impedance bandwidth. Based on the parametric study, it is found that scaling the base of an upper triangular slot with reference to a simple tetrahedron base does not significantly affect the impedance bandwidth. So, the scaling value (c_2/c) of 0.2 is fixed considering ease of fabrication.

The position and height of a coaxial probe play crucial roles in impedance matching and bandwidth improvement. It is observed that as the probe height is increased from 6 mm to 12 mm, bandwidth improvement is achieved. The effect of probe height on bandwidth of proposed DRA is plotted in

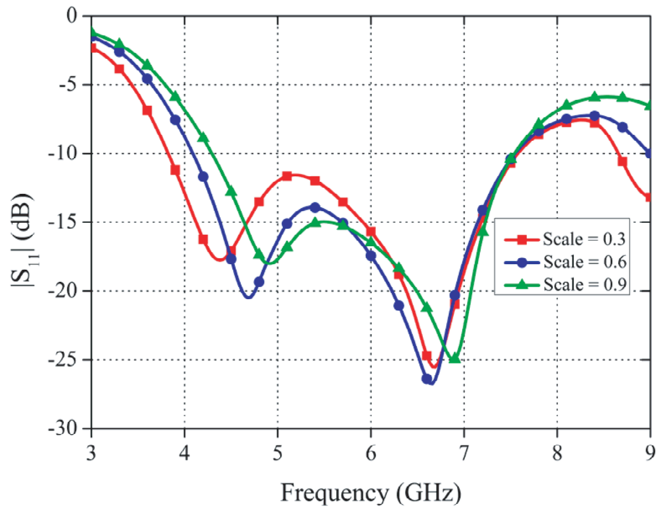

Figure 4. Return-loss performance of first iteration DRA design for different scaling.

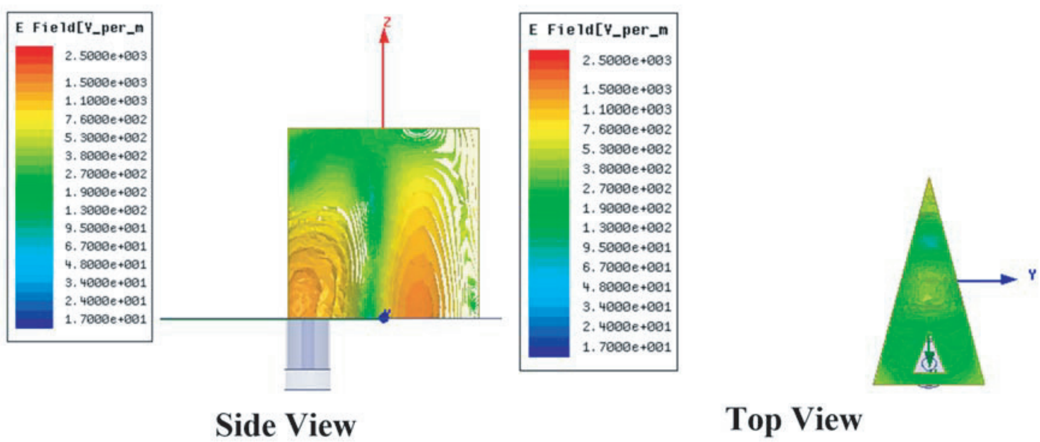

Figure 5. Internal electric field distribution in first iteration tetrahedron DRA at 8 GHz.

Fig. 6.

Improvement in bandwidth achieved by transition from a simple tetrahedron DRA to the proposed DRA is shown in Fig. 7. Based on the promising simulated results, it was decided to fabricate the antenna. The fabricated antenna was tested for return-loss performance using a Network Analyzer. Fig. 8 shows photographs of a fabricated antenna from different angles. The comparison between the simulated and measured return-loss performances is plotted in Fig. 9. It is clear that the measured results are in agreement with the simulated ones. About 72.3% measured impedance bandwidth is achieved. The DRA height of 19 mm is achieved by stacking 15 DR material strips of 1.27 mm each. Adhesive having permittivity about 3 is used to bind the DR strips together. It is believed that this thin layer of adhesive is responsible for reduction in return-loss performance. Also, a slight shift in frequency to the left is seen in the measured results due to the change in the location of a feed. Thus, misalignment in feed location and use of adhesive have contributed in frequency shift and reduction in return-loss performance.

The impedance bandwidths of iterative designs are summarized in Table 1. Bandwidth improvement from 47.4% to 72.3% is achieved by introduction of fractal triangular slots at appropriate locations. Simulated gain and radiation efficiency of the first iteration DRA and proposed DRA are shown in Figs. 10 and 11, respectively. Average gain in the range of 5.5–7.5 dBi and about 98.2%

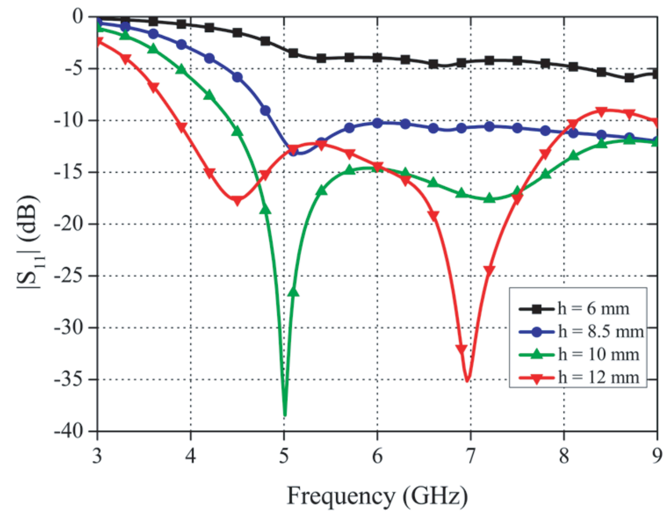

Figure 6. Effect of probe height on bandwidth performance of proposed DRA.

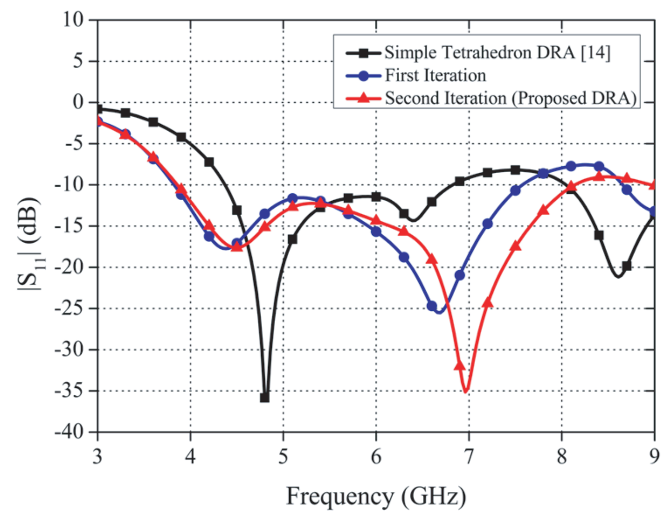

Figure 7. Comparison of iterative return-loss performance.

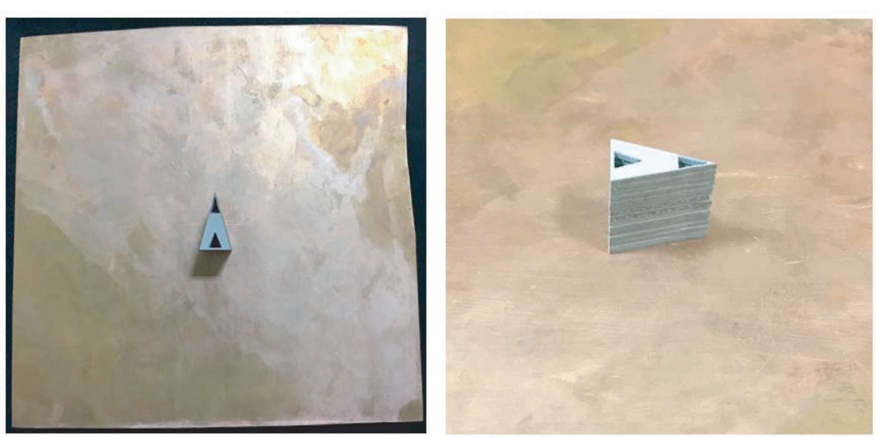

Figure 8. Photographs of a fabricated antenna.

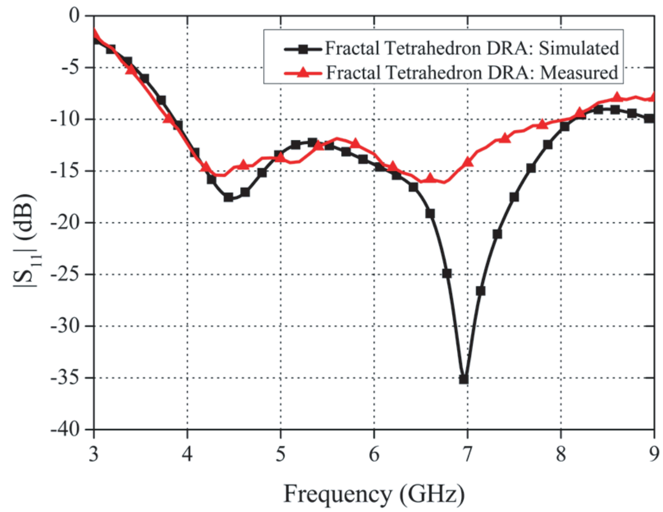

Figure 9. Comparison of the simulated and measured return-loss performance of proposed DRA.

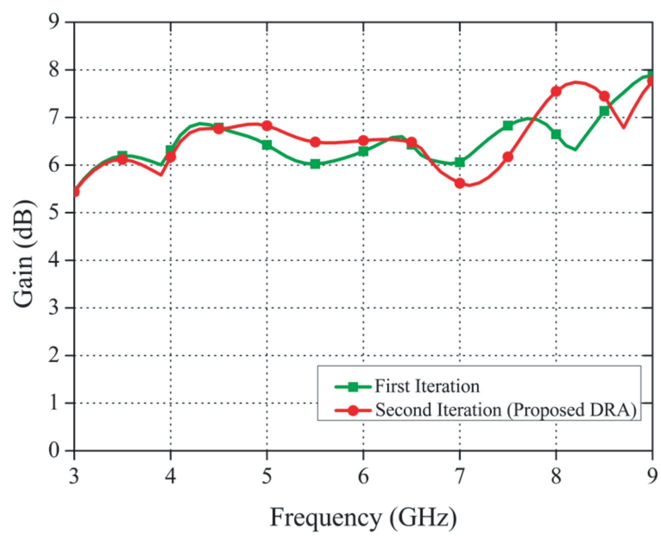

Figure 10. Comparison of iterative gain performance.

Table 1. Comparison of impedance bandwidths.

DR Geometry	**% Bandwidth (−10 dB Reference)**
Simple Tetrahedron DRA [17]	47.4%
First Iteration (Proposed DRA design): Simulated	66.2%
Second Iteration (Proposed DRA design): Simulated	77.6%
Second Iteration (Proposed DRA design): Measured	72.3%

radiation efficiency are achieved over the entire band of interest for the proposed DRA.

The simulated co- and cross-polarized radiation patterns in E- and H-planes at 5.3 and 7 GHz, respectively, are shown in Fig. 12. From the graphs, it is clear that about 20 dB separation in broadside direction between co- and cross-polarized fields is achieved.

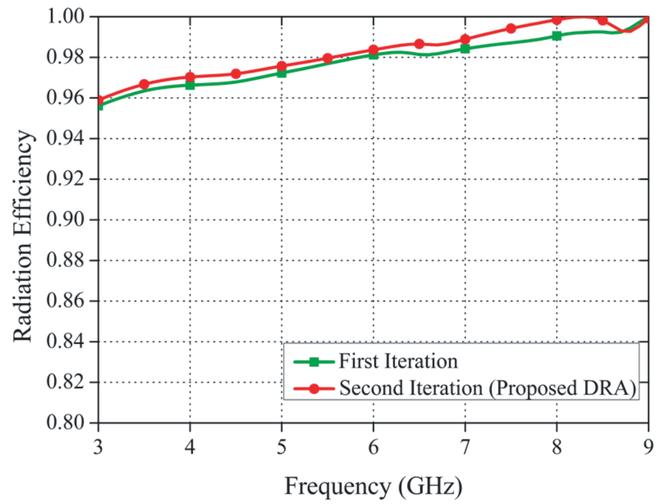

Figure 11. Comparison of iterative radiation efficiency.

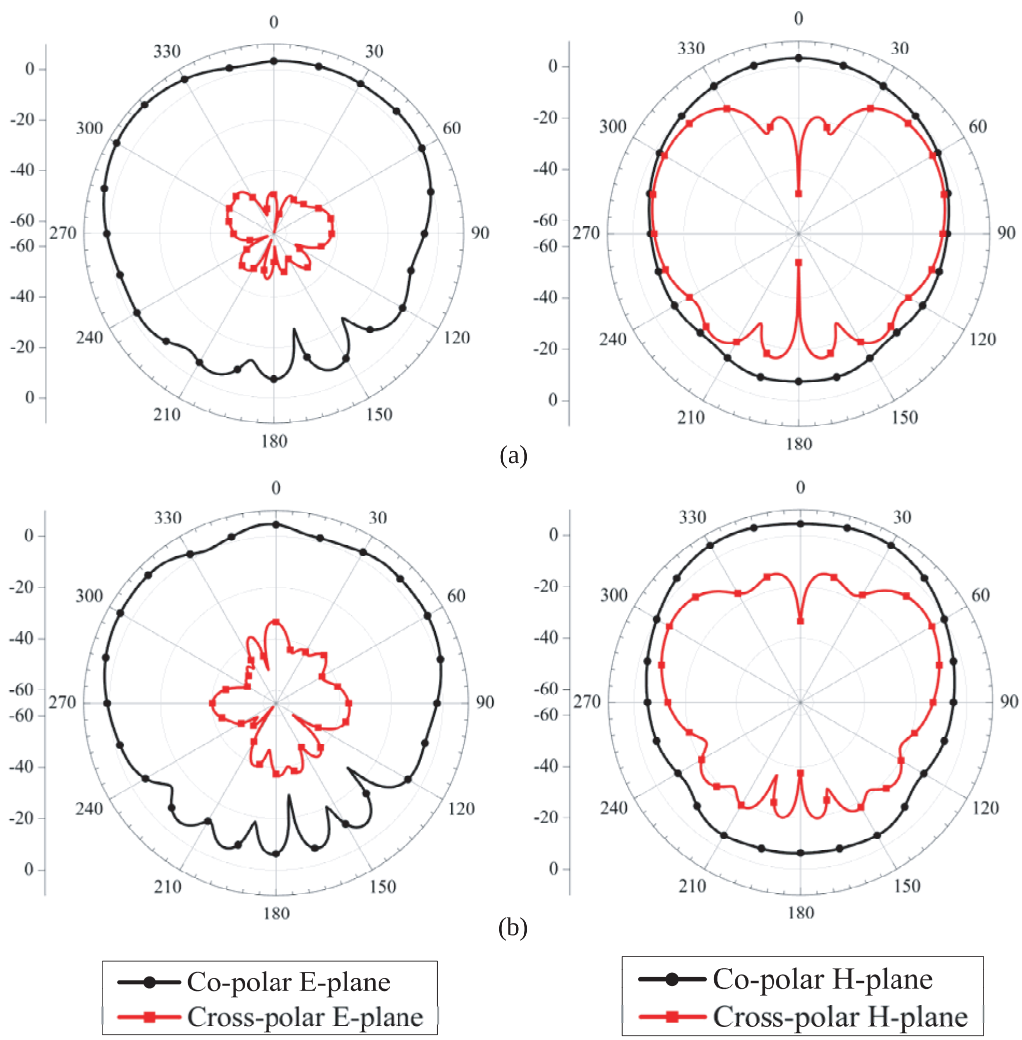

Figure 12. Simulated co-polarized and cross-polarized radiation patterns of proposed DRA at (a) 5.3 GHz, and (b) 7 GHz.

4. CONCLUSIONS

In this paper, the design of a tetrahedron DRA with fractal triangular slots is proposed. Internal coaxial feeding is used for better impedance matching. Based on the parametric analysis and experimental study of the proposed design, it can be concluded that bandwidth can be improved by introducing fractal triangular slots in a tetrahedron DRA. The proposed design offers 72.3% measured impedance bandwidth. Also, broadside radiation pattern, with average gain in the range of 5.5 to 7.5 dBi over the band of interest, is achieved. The proposed design gives good radiation efficiency of the order of 98.2% and shows significant bandwidth improvement in comparison to a design proposed in [17]. Further, it is observed that inaccurate machining, lossy connectors, adhesive losses, and misalignment of feed can degrade the overall performance of the antenna. Looking to the broad band performance and gain, the proposed antenna can be a good option for its use in wideband applications.

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