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Triple Band Circularly Polarised Hexagonal Shaped Dielectric Resonator Antenna for Multi Band Applications

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Abstract: This article epitomize a triple-band circularly polarized (DRA) dielectric resonator antenna. The proposed DRA works on the fundamental mode TE_{xyz}, i.e., TE_{111} and consecutively on higher order modes, i.e., TE_{113} mode and TE_{115} mode of the DRA for the triple band. The antenna is excited by means of aperture coupled fields. For circular polarization, dielectric resonator antenna is cut by edges of 45 degree on both sides rectangular dielectric resonator antenna with a stair shaped slot on the ground plane for triple band operation. For low reflection coefficient, metal strips of low heights are provided at the base of substrate. Also, the substrate is formed by using two layers of substrate of FR4 epoxy (ε_r = 4.34) and RF35 (ε_r = 3.4) to achieve three degenerate orthogonally modes TE_{111}, TE_{113} and TE_{115}. Antenna is hexagonal in shape with the material alumina having dielectric constant (ε_r = 9.92). Range of the operating frequency is as 2–4, 4–8 and 8–12 GHz with the corresponding circular polarization. The calculated impedance bandwidth for return loss is 9.7, 5.41 and 11.07%, respectively. The calculated bandwidth for (LHCP & RHCP) axial ratio is 3.40, 0.4 and 2.3% correspondingly to the band of antenna. The other DRA parameters calculated are reflection coefficient and gain which are in permissible limits. The antenna has the application for the bands of S, C and X band for the Weather RADARs, Wi-max, Bluetooth, military and space applications. Antenna is simulated using ANSYS HFSS and also antenna is fabricated and tested using VNA.

Keywords: Dielectric resonator antenna; Dual band; Circular polarisation; High gain; Reflection coefficient

1. Introduction

From past few decennium in wireless communication systems, dielectric resonator antennas (DRAs) [1, 2] have come out with appealing advantage over other traditional antenna's. Attractive features like light weight, small size, low cost, supremacy in structure, different shape like cylindrical, spherical, hemi spherical [3] rectangular, etc., gives researcher a free hand to modernize the antenna system with wide bandwidth, high gain and low axial ratio [1, 2, 4–6]. Presently there is a need of antenna having low axial ratio, i.e., circularly polarised (CP) antenna as there is not limitation in propagation effect and misalignment of the antenna. A number of circularly polarised antennas have been presented [7–13] but all of them are limited to single band investigations only. Stacking of the antenna with different dielectric constant prove to combine advantage of different material application in one in the parameter of high gain [14] and wider bandwidth [15, 16]. Depending on the application needed, different studies have been combined to give commutated result of advancing different parameters [17]. Slot shape on the ground plane gives advances in the better axial ratio, e.g., stair shaped slot, rotation of the slots [18–20], bandwidth controlled [21]. With the time several methods have been proposed in order to achieve low axial ratio and high impedance axial ratio bandwidth. Two substrate method have been proposed for low axial ratio [22], use of metallic strips [23], lattice structure [24], hollow cylinder [25] are some of methods.

With the development in communications systems [26] over time, complexity in the system have been increased hence, there is a need of multi band antenna with wider impedance bandwidth besides wide axial ratio bandwidth.

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In this article, we target to achieve triple band antenna with low return losses and circularly polarised antenna. For this, we have used a concept of lattice structure with stacking in the stacked dielectric resonator antenna in order to achieve low return losses. For circular polarisation stair shaped slot [18] have been used. A step by step parametric study have been done and collectively on the basis of different aperture couple feeding mechanisms and formulations a design has been achieved on hexagonal DRA using stack formation working on triple band (2–4) GHz, (4–8) GHz, and (8–12) GHz, covering, S, C and X band. Besides low return losses proposed antenna is showing low 3 dB axial ratio. LHCP (left hand circular polarisation) and RHCP (right hand circular polarisation) contributing the total axial ratio bandwidth as 3.40, 0.4 & 2.3% and impedance bandwidth 9.7%, 5.41% and 11.07% for the respective bands. Simulation of the antenna is done using software tool ANSYS HFSS (high frequency structure simulator), further a prototype model has been fabricated and tested using a VNA (Vector Network Analyser).

2. Antenna Structure

The antenna design consists of two lattice structure substrate of FR4 epoxy of permittivity ($\varepsilon_{r1} = 4.34$) and RF35 of dielectric constant ($\varepsilon_{r2} = 3.4$) of the dimension (LxWxH) shown in the Fig. 1 and dimensions measurement mentioned in Table 1. Top view of the antenna is shown in Fig. 2. On the substrate of the antenna, a stair shaped slot has been introduced for energy transmission to the dielectric material. Antenna consists of hexagonal shaped dielectric material alumina (Al_2O_3) of thermal conductivity 35 W/mK, tensile strength 275 MPa and loss tangent 0.0001. On the top a small of metallic conductor is placed in order to improve the gain of the antenna. A detailed parametric study is being done to improvise the result of the antenna. To provide the isolation to the antenna from external interference, metallic side walls is introduced of small height as mention in the table and shown in Figs. 1 and 2.

Table 1 Dimensions for the slot on ground plane

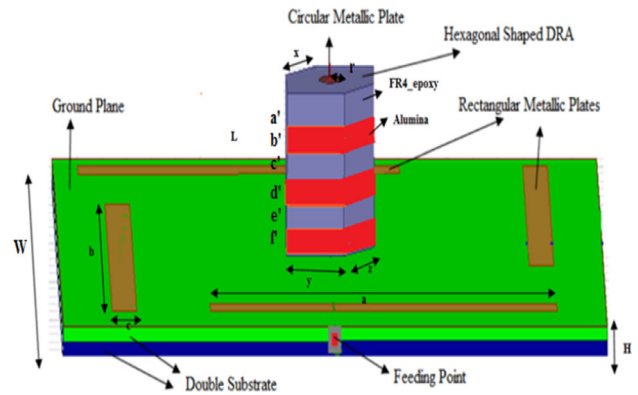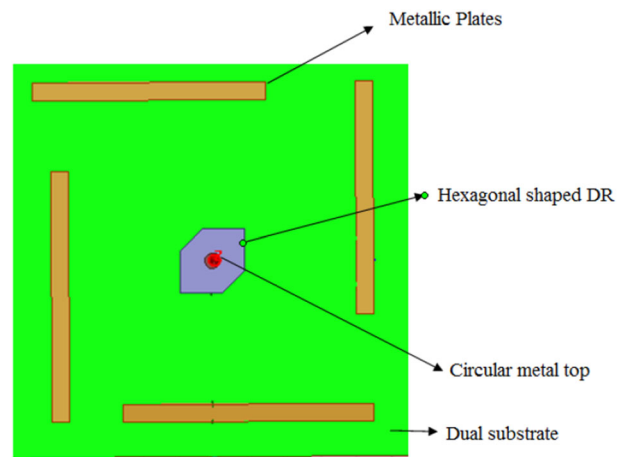| S. No	Element symbol	Dimension (mm)
1	a'	7.9
2	b'	2.2
3	c'	4.3
4	d'	3.6
5	e'	4.3

Fig. 1 Side view antenna structure with dimension

Fig. 2 Top view of the antenna

Slot on the ground plane is calculated [17]

$$l_s = S_1 = S_2 = 0.4 \lambda o \sqrt{\in_e} \tag{1}$$

$$\in_{\text{eff}} = (\in_s + \in_r)/2 \tag{2}$$

The general expression for TE_{xyz} the resonant frequency [17] for the higher order modes is

$$f_0 = \frac{c}{2\pi\sqrt{\in_r}}\sqrt{k_x^2 + k_y^2 + k_z^2},$$
$$k_x = \frac{\pi}{a},$$
$$k_z = \frac{\pi}{2b}, \tag{3}$$

$$d = \frac{2}{k_y}\tanh\left(\frac{k_{y0}}{k_y}\right), \; k_{y0} = \sqrt{k_x^2 + k_z^2}, \tag{4}$$

where,

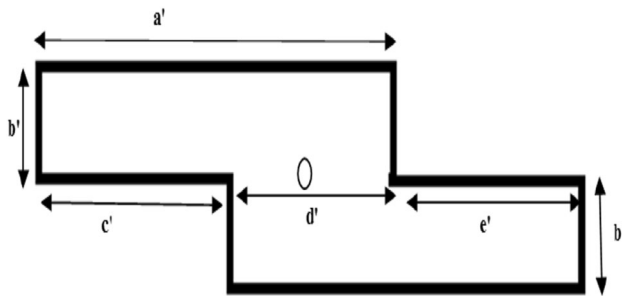'C' is the velocity of light.

Expanding Binomial Expression,

Fig. 3 Stair shaped slot of the proposed antenna

Fig. 4 Return loss (dB) versus frequency (GHz) for the simulated and experimental result for S band

Table 2 Dimension of proposed Antenna

S. No	Name of element	Dimension (mm)
1	Ground plane $(L \times W)$	80×80
2	Substrate Height, H	1.62
3	Diameter of cylindrical cap, $2r$	1.2
4	Length of metallic plates, $a = b$	46
5	Width of metallic plates, c	8
6	Height of metallic plate, h	12
5	Microstrip length, l_m	48.64
6	Microstrip width, w_m	1.58
7	Stub length, s_l	4.64
8	Total height of Hexagonal shaped DR, h'	16.8
9	No. of stacking of DR	6
10	Each side of hexagonal DR	9.2

Fig. 5 Return loss (in decibels) versus frequency (in GHz) for the simulated and measured result for C band

$$k_y \tan\left(\frac{k_y d}{2}\right) = \sqrt{(\in_r -1)k_0^2 - k_y^2}$$

Also,

$$k_y b + 2\tan^{-1}\left(\frac{k_y}{k_{y0}}\right) = n\pi \qquad (5)$$

where, $k_{y0} = \sqrt{(\in_r -1)k_0^2 - k_y^2}$

$$k_y b + 2k_y\left(\frac{\sqrt{(\in_r -1)k_0^2 - k_y^2}}{(\in_r -1)k_0^2}\right) = n\pi \qquad (6)$$

Therefore,

$$k_y = \frac{n\pi}{b\left[1 + 2\left(\frac{1}{bk_0\sqrt{(\varepsilon_r -1)}}\right)\right]} \qquad (7)$$

$k_y = \frac{n\pi}{b}$, where $\hat{b}$ is Effective width.

And mathematically,

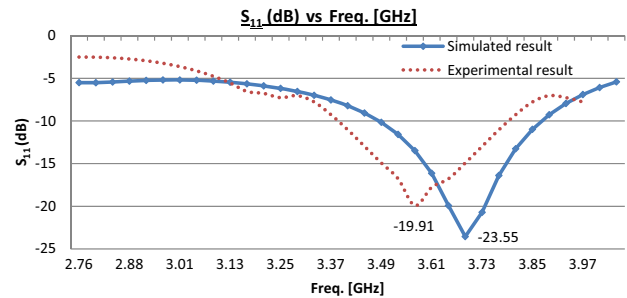$$\hat{b} = b + \left(\frac{2}{k_0\sqrt{(\varepsilon_r -1)}}\right)$$

The stair shaped slot is fabricated at top of ground plane as shown in Fig. 3, and a *50 Ω* microstrip feed line is attached on the other side of substrate. The dimensions of the slots are calculated using RDRA [17] feed line formula. Later on parametric study for circular polarisations is done. Each substrate is of 0.81 mm. Total height of substrate is 1.62 mm. While length of the substrate is length, $L = 80$ mm and width, $W = 80$ mm. Similarly total height of the antenna material is 16.8 mm. For stack purpose introducing six layers, dividing the total height of antenna in six segments of (*a, b, c, d, e, f*) each of height 1.8 mm (*h' = a' + b' + c' + d' + e' + f'*) Red colour stack is of alumina (*ε = 9.92*) and blue colour stack is of FR4_epoxy. The geometry of the antenna is hexagonal shaped DRA, with all sides equal and placed on a ground plane having a stair shaped slot. A metallic cap is placed on the top of dielectrics antenna of diameter 1.2 mm. In Figs. 1 and 2 design of proposed antenna is shown as side view and top view with details.

Stair shaped slot on the ground plane is shown in Fig. 3 Dimension of the antenna in tabular form in Table 2.

Mathematically, using the equation (i), (iii), (iv) and (v), the resonant frequency for the antenna for above dimension and using transcendental equation for higher modes, i.e., (TE_{111}, TE_{113}, (TE_{115}) are as following,

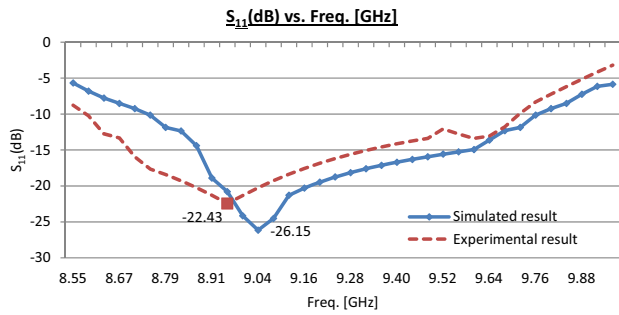For, TE_{181}, $f_o = 3.72$ GHz, $TE_{183} = 5.20$ GHz, $TE_{183} = 9.10$ GHz.

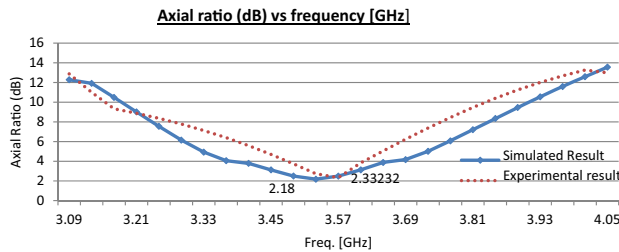**Fig. 6** Return loss (dB) versus frequency (GHz) for the simulated and measured result for X band

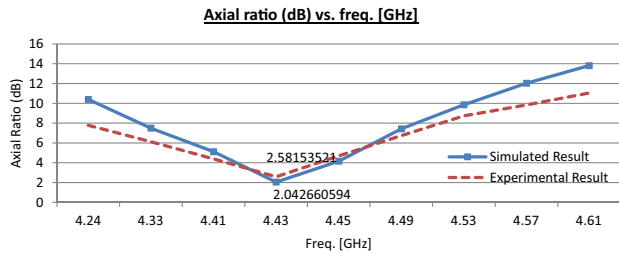**Fig. 7** Axial ratio (dB) versus frequency for the simulated and measured result for S band

Fig. 8 Axial Ratio (dB) versus frequency (GHz) for the simulated and experimental result for C band

3. Results and Discussion

3.1. Return Loss

The antenna structure and geometry are discussed in above section with detailed diagrams. The return loss of the simulated proposed antenna is working in three bands with acceptable parameters result. The centre frequency is 3.68 GHz (3.48–3.84), 5.17 GHz (5.05–5.33) and 9.03 GHz (8.75–9.75). The multi band antenna proposed in this article combines the advantages of three antenna used for three different band, i.e., S, C, X band applications. The antenna is having low axial ratio (< 3) in all three bands.

Detailed analysis is done on the basis of parametric analysis of the antenna. Effect of side walls, effect of different slot size and its impact is studied. And based on the
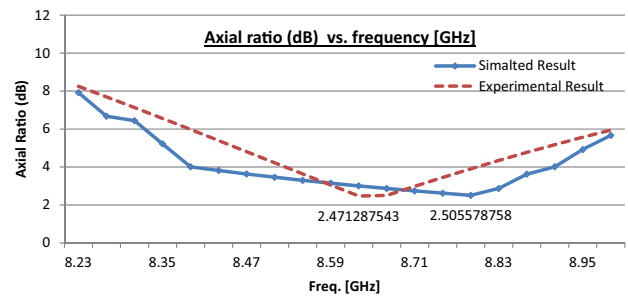

Fig. 9 Axial Ratio (dB) versus frequency (GHz) for the simulated and experimental result for X band
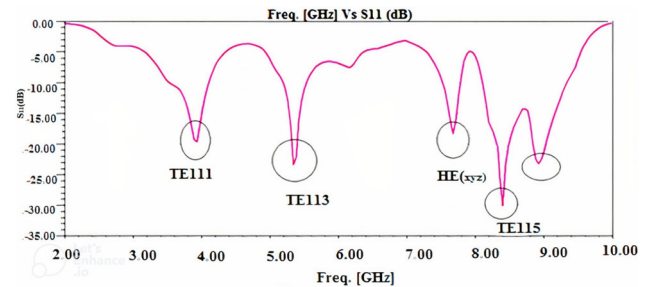

Fig. 10 Combined simulated result for return loss (dB) on all three bands

study done, best method is analysed for triple band DRA with low axial ratio. Antenna is fabricated using the photolythic method, and with the help VNA antenna is tested.

In Fig. 4 results for return loss in terms of scattering parameters (S_{11}) in decibels (dB) with the variation in frequency (GHz). The simulated result using the software simulator (HFSS) and experimental result using VNA have been plotted. The antenna for transmission of EM waves is workable when S_{11} is less than -10 dB. By analysing the plotting region of the curve, return loss for simulation is having ($S_{11 <} -10$ dB) in (3.48–3.84) GHz and impedance bandwidth of 9.7%, with the dip of return loss at 3.68 GHz with -23.55 dB. While the experimental result also showing the satisfactory result with similar to simulation result. With this antenna can be operating in the S band (2–4 GHz) applications.

In Fig. 5 graph of return loss is shown in (dB) and frequency in (GHz). The simulated results are compared with experimental result. The antenna is working in C band (4–8 GHz) applications. The simulated results are working ($S_{11} < -10$ dB) in the range of frequency 5.05–5.33 GHz with the centre frequency at 5.17 GHz with S_{11} value as -24.96 dB and the impedance bandwidth is 5.41%.

Comparison graph of experimental result and simulated result is shown in Fig. 6 for third band of the antenna. The Scattering parameters is < -10 dB for 8.75–9.75 GHz with the dip of return loss at 9.03 GHz at -26.15 dB.
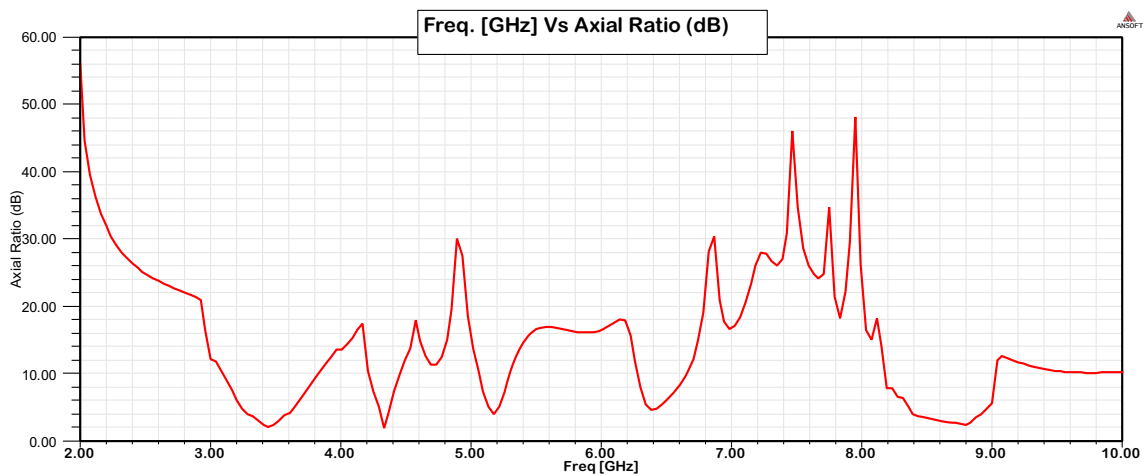
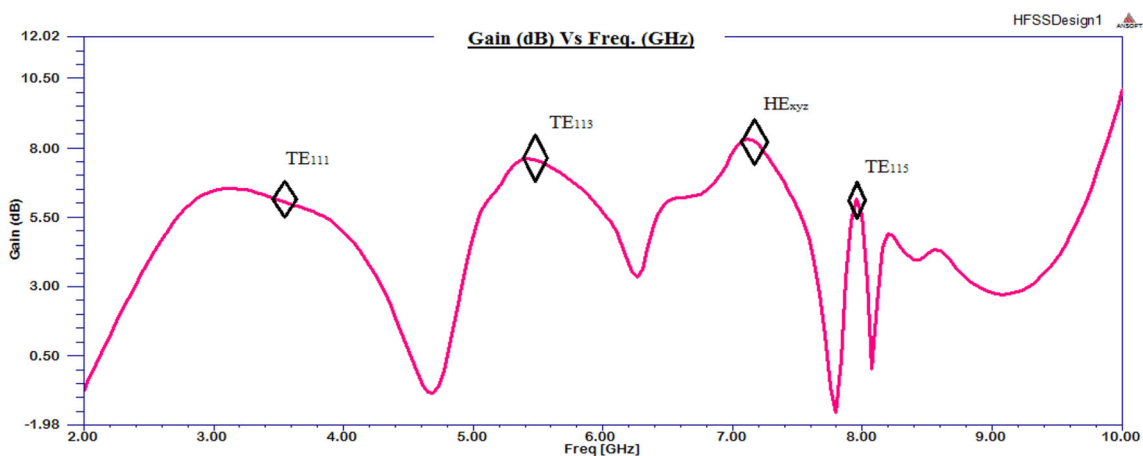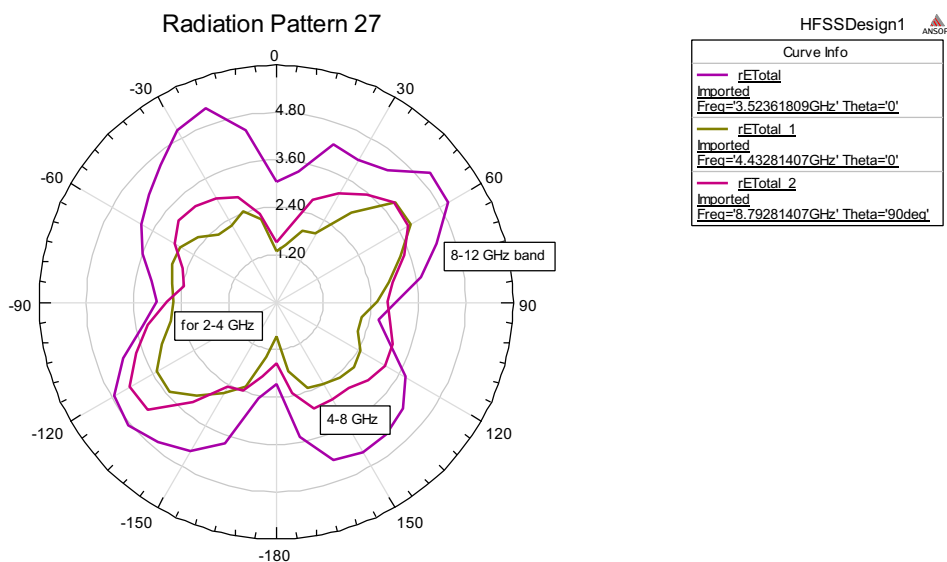**Fig. 11** Combined simulated result for axial ratio (dB) on all three bands

Fig. 12 Combined simulated result for Gain (dB) of all three bands

Fig. 13 Combined simulated result for radiation pattern of all three bands

Hence, the impedance bandwidth of 11.07%. The antenna can operate in X band applications.

3.2. Axial Ratio

Circular polarization is one of the important and desirable parameter in communications system. Circular polarization is measured in terms of axial ratio. Desirable value for axial ratio is less than 3 dB. Axial ratio is the ratio electric field in x-axis direction to the electric field in y-axis direction (E_x/E_y). The circular polarization (TE_{xyz}) is in terms of LHCP (left hand circular polarization) and RHCP (Right hand circular polarization). The effect of stair shaped slot used is easily seen in the axial ratio results.

In Fig. 7, the axial ratio with respect to corresponding frequency is being plotted with the comparison with simulated result and experimental result. The acceptable value for the axial ratio is the (< 3 dB). The axial ratio for simulated result is from 3.46 to 3.58 GHz, with the antenna maximum polarized at 3.52 GHz having axial ratio value as 2.17 dB (0.12 GHz) and the total axial ratio bandwidth is 3.40 dB.

Comparison graph of axial ratio of simulated result and experimental result is shown in Fig. 8. The value of axial ratio is from 4.42 to 4.44 GHz with the centre frequency at 4.43 GHz with the value of 2.04 dB and total axial ratio bandwidth is 0.4%.

Figure 9 shows the graph of axial ratio with frequency of the simulated result and experimental result. The axial ratio is 8.64–8.85 GHz (< 3 dB). The maximum CP achieved is 2.50 dB at 8.79 GHz.

4Combined graph of simulation result using HFSS simulator is shown in Fig. 10 with all range of three band (2–4), (4–8) & (8–12) GHz frequency on same graph. Higher order modes are achieved on subsequent frequencies TE_{xyz} (TE_{111}, TE_{113}, TE_{115}) is clearly seen in the

graph. The graph is of return loss in decibels and frequency in GHz.

Figure 11 shows the plotting of combine graph of axial ratio and frequency graph, showing the circular polarization at different frequency.

Figure 12 shows the combined graph of the gain in decibels with respect to corresponding frequency in Giga Hertz. The antenna gain specifies that how much proposed antenna takes over while converting the power as input into radio waves in the specified direction.

The simulated value for the gain is 5.80 dB at 3.68 GHz, 6.12 dB at 5.17 GHz and 5.40 dB at 9.03 GHz.

In Fig. 13 combined radiation pattern of DRA is shown. Radiation pattern on all three centre frequency is plotted.

The radiation pattern is the far field graphical representation of the energy transmitting from the antenna.

($r > > 2D2/\lambda$), where D is the largest dimension antenna [17]

In Table 3, results achieved for the DRA in tabular form for comparison with the work already done in various reputed journals. As seen, in table form, the design of the antenna in this paper showing better result in terms of gain of the antenna and return loss of the antenna hence, increasing the performance of the antenna.

Comparison of the results obtained from simulation and experimentation of the proposed antenna is shown in Table 4.

Antenna is fabricated using the photolythic method. Later on successful fabrication for verification of the simulated results, hardware of the antenna is tested using the set up VNA (vector network analyser). Figure 13 displays the prototype model of the proposed antenna. Figure 14 displays the return loss vs frequency output screen of the VNA showing the triple band functioning of the antenna. The deviation between the simulated result and experimental result is due to manually cutting the dielectric

Table 3 Simulated Results of the proposed antenna

S. No	Band	B.W (GHz), F_H-f_L	Centre frequency, f_o (GHz)	S_{11} (dB) (lowest)	Impedance bandwidth (%)	Axial ratio (MHz)	Centre frequency (GHz)	Axial ratio (%)
1	S	0.44	3.68	−23.55	9.7	120	3.52	3.40
2	C	0.28	5.17	−24.96	5.41	122	4.43	0.4
3	X	1.0	9.03	−26.15	11.07	210	8.79	2.3

Table 4 Simulated result versus Experimented result of the proposed antenna

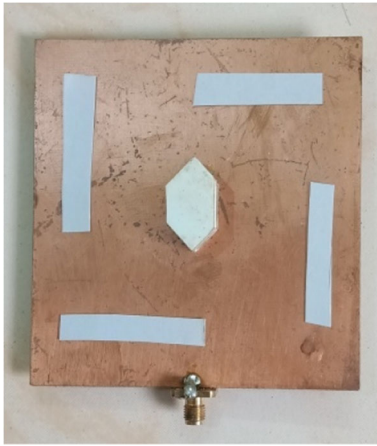| S. no	Simulated results			Experimented result		
	Freq. (GHz)	S_{11} (dB) (at centre freq.)	Axial Ratio (dB)	Freq. (GHz)	S_{11} (dB) (at centre freq.)	Axial Ratio (dB)
1	3.48–3.84	−23.55	2.18	3.46–3.58	−19.91	2.33
2	5.05–5.33	−24.96	2.04	4.42–4.44	−21.28	2.58
3	8.75–9.75	−26.15	2.51	8.64–8.85	−22.43	2.47

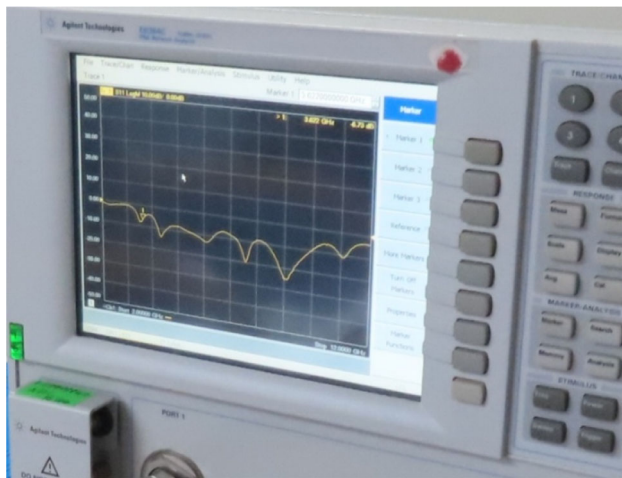**Fig. 14** Fabricated model of proposed antenna

Fig. 15 Experimental results

resonator material, which is like hard marble, instrumentation error, and other human error (Fig. 15).

4. Conclusion

The proposed antenna in this article shows the acceptable results with low return losses ($S_{11} < -10$ dB) in all three bands of S, C and X band with having low axial ratio (< 3 dB), criteria to calculate circular polarisation. After parametric analysis on different segments of the antenna, like effect generated by dual substrate, stacking of the hexagonal shaped DR, shape of the DR, effect of metallic plates, effect of slot shaped, result is concluded in a systematic way to achieve impedance bandwidth of 9.7, 5.41 and 11.07%, respectively. The axial ratio bandwidth (LHCP & RHCP) is 3.40, 0.4 and 2.3% correspondingly to the band of antenna. Such antenna is very much useful in a multi band applications of corresponding desirable band.

With the application of satellite communication, Weather RADARs, consumer base appliances, weather forecasting and defence base applications.

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