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Dimensions Selection Criteria of Stair-shaped Slot for Obtaining the Wideband Response of CPDRA

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ABSTRACT

The analysis of a circularly polarised (CP) dielectric resonator antenna (DRA) with the aperture coupled feeding technique is presented in this paper. Until now, the random techniques have been developed for obtaining the CP response in DRA. It is glaringly required to develop a fixed mathematical criterion for the selection of dimensions of the antenna structure. The criterion for selection of the stair-shaped slot dimensions, which is utilised for obtaining the CP response, is defined in this paper. The ranges of slot length ratios are investigated so that a wide CP bandwidth can be obtained. The antenna offers the 10-dB impedance bandwidth of 58.62 per cent (4.1 GHz - 7.5 GHz) and 3-dB axial ratio bandwidth of 40.86 per cent (4.26 GHz - 6.385 GHz).

Keywords: Circular polarisation; Criterion; Dielectric resonator antenna

1. INTRODUCTION

The dielectric resonator (DR) antenna (DRA) offers the low conductor and surface wave losses and improved radiation performance[1]. Till now, different DR shapes have been reported[1]. The rectangular shaped DR is simplest and provides more flexibility in selection of the resonant frequency[1]. Initially, the study was limited to linearly polarised (LP) antennas only. The LP antennas have the losses due polarisation mismatch and multipath reception. To suppress these limitations, circularly polarised (CP) antennas are the suitable choice[2].

A number of CPDRAs have been implemented and reported in the literature[3–10]. A brief categorisation of these antennas based on their DR shape and feeding mechanism has been reported in[2]. The simplest structure of CPDRA is with regular shaped DR and single feeding structure but it provides the narrow bandwidth[3,4]. The CP bandwidth has been enhanced by dual-feeding mechanism but it creates the structural complexity[5]. Some CPDRAs were also reported with specific DR geometry and single feeding structure, providing wide axial ratio (AR) and impedance bandwidth like stair shaped[6], rotated stair[8], trapezoidal DR[9], fan-blade-shaped DR[11], inverted sigmoid-shaped DR[12] and DRA with inclined slits in diagonal of the DR[10]. The fabrication of the CPDRA with specific geometry is quite difficult because DRs are made of ceramics which cannot be cut with precision due to hardness of the material. To avoid the modifications in the DR shape, some CPDRAs were proposed with different shapes of the slot in the ground plane[4,13,14].

In the literature, the random techniques have been implemented and reported to obtain the CP response in DRA. It is prominently required to develop a fixed mathematical criterion for selection of the dimensions of the antenna structure. Recently, the wideband CPDRAs with stair-shaped slot were reported[2,15]. However, the criteria for selection of the dimensions of the stair shaped slot is not reported in these papers. The criterion for selection of the dimension is defined in this paper so that a wide CP bandwidth can be obtained. The proposed research paper can be a basis for the industries seeking for the solution of designing a wideband CPDRA.

2. DESIGN, CONCEPT AND ANALYSIS

A rectangular DR having volume $a \times b \times d\ mm^3$ is kept on the ground plane. The ground plane is placed above the substrate of material FR-4 epoxy ($\epsilon_s = 4.4$) with volume $l \times w \times 0.8\ mm^3$. This DR is excited through a rectangular slot of dimension $l_s \times w_s$ and 50Ω microstrip line with stub of length s. This antenna provides the LP radiation and operates with fundamental mode at 4.7 GHz. The changing the shape of the slot as a stair with side slots of length and width s_1, s_2 and width w_s', respectively as depicted in Fig. 1 provides the CP response. Figure 2 shows the physical concept behind the operation of the CP antenna. The stair-shaped slot splits the *E*-field into two orthogonal components with nearly equal amplitude, which results in CP radiation. HFSS is used for the analysis of antenna.

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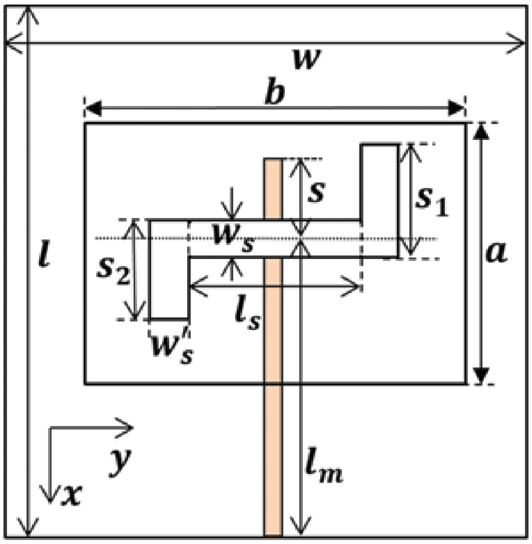

Figure 1. Proposed antenna geometry.

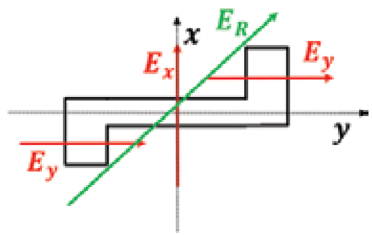

Figure 2. The physical concept of the antnena operation.

2.1 Procedure to Select the Length of Slots

For the DR with $b/a = 1.357$ and $h = 0.078\lambda_o$ operating with fundamental mode at frequency around 4.7 GHz, dimensions of the slots are selected based on formulae as-

i. The main rectangular slot length is calculated using formulae given in (1)[16].

$$l_s = \frac{\lambda_g}{2}; \quad \lambda_g = \frac{\lambda_0}{\sqrt{\epsilon_{eff}}}; \quad \epsilon_{eff} = \frac{\epsilon_r + \epsilon_s}{2} \tag{1}$$

ii. Length of the side slots is calculated using (2)[16].

$$s_1 = s_2 = \frac{\lambda}{\sqrt{\epsilon_{eff}}} \tag{2}$$

iii. The width of the slots are selected as $w_s \square\, l_s$ and $w_s' \square\, (s_1 + s_2)$. Generally, (*width of the slot* $0.2\times$ *length of the slot*)[16].

iv. λ_o is free space wavelength.

Initially, the stair-shaped slot is selected symmetrical about the centre with the calculated lengths of the slots as $l_s = 11$ and $s_1 = s_2 = 7\ mm$. The lengths of the slots are then optimised to find wideband CP response. The value of l_s is extended to 13 *mm* with $s_1 = s_2 = 8.5\ mm$ this combination of the slot dimensions provides the wide AR bandwidth. With asymmetrical slot $l_s = 13,\ s_1 = 10.1,\ s_2 = 7\ mm$, a wide CP bandwidth is achieved in comparison to the symmetrical slot.

In both the cases (either symmetrical or asymmetrical), the lengths of the side slots are selected such that the sum of s_1 and s_2 remains near to $0.25\lambda_g$ $(s_1 + s_2 + \approx 17\ mm)$ and $l_s = 0.2\lambda_g$ $(l_s = 13\ mm)$. To find the wide CP bandwidth, two conditions must be satisfied simultaneously:

i. The ratio of the side slot lengths s_1/s_2 should remain in the range of $1.0 - 1.4428$ (keeping $s_1 + s_2 \approx 17\ mm$).

ii. The ratio $(s_1 + s_2)/l_s$ should remain in range of 1.21-1.34.

If DRA is designed considering these conditions, a phase difference of 90° is obtained between the degenerate modes. The best suitable choice of the slot length ratio $(s_1 + s_2)/l_s$ is closest to 1.31 in both the cases.

Figure 3(a) and (b) shows the antenna response with the excitation through rectangular and stair-shaped slot ($s_1 = 10.1,\ s_2 = 7.0$). The impedance bandwidth remains same in both the cases. The AR is above 40 dB with rectangular slot and it goes below 3 dB with the stair shaped slot. Figure 3(c) and (d) represents the S_{11} and AR frequency response with the different set of slot dimensions. The asymmetrical stair-shaped slot provides the wider CP bandwidth. The geometrical parameters with optimised values are; $a = 24, b = 33, h = 5, l_s = 13, w_s = 1.5,$ $= 80, w = 80, l_m = 40, w_m = 1.6, s = 7.0, s_1 = 10.1, s_2 = 7.0$ and $w_s' = 2.5$; unit of dimensions is *mm*. Figure 4 shows the fabricated antenna prototype.

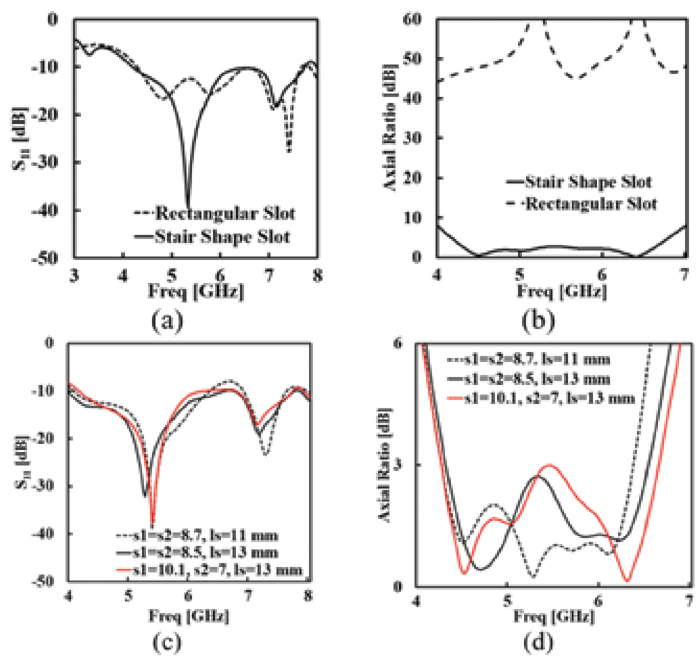

Figure 3. (a) S_{11}, (b) AR response with rectangular and asymmetrical stair-shaped slot, (c) S_{11} and (d) AR response for different dimensions of the stair-shaped slots.

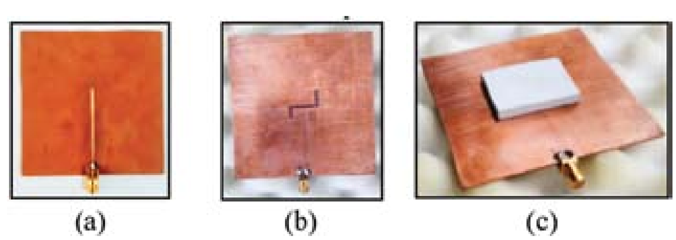

Figure 4. Fabricated antenna prototype (a) bottom (b) top and (c) side view.

2.2 Theoretical Analysis of Circular Polarisation

The mode at frequency 4.5 and 5, 5.8 and 6.3 GHz are identified as quasi TE^{y}_{111}, TE^{x}_{111}, TE^{y}_{221} and TE^{x}_{221}, respectively. The antenna provides the CP radiation at 4.74 and 6.02 GHz due to first and second order modes, respectively. Figure 5 shows the *E*-field analysis in $z = d$ plane at 4.74 and 6.02 GHz with phase angle $45°$ and $-45°$. Figure 6 shows the *E*-field in same plane at the frequency of resonant modes. The *E*-field shown in Fig. 6 corresponds to Fig. 5, which confirms the 90° phase difference between the degenerate modes.

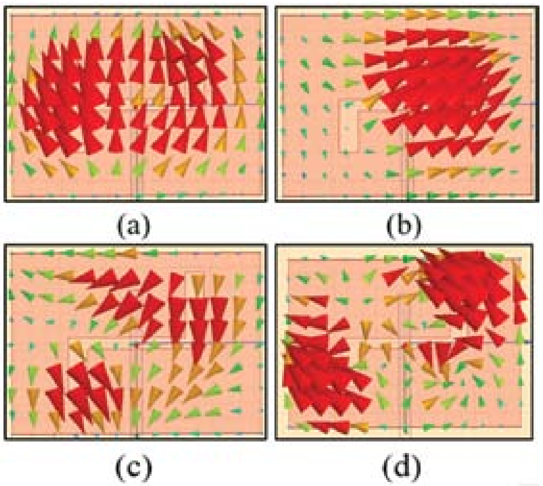

Figure 5. *E*-field analysis a 4.74 GHz (a) $\angle 45°$ (b) $\angle -45°$ and 6.02 GHz (c) $\angle 45°$, and (d) $\angle -45°$.

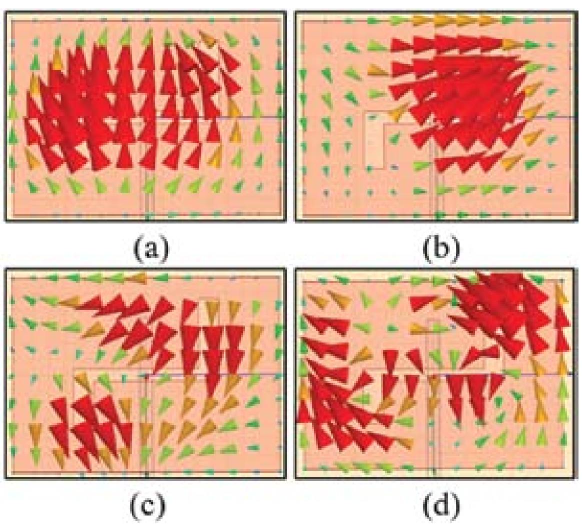

Figure 6. *E*-field analysis at (a) 4.5, (b) 5, (c) 5.8 and, (d) 6.3 GHz.

3. PARAMETRIC STUDY

The effect of a, b, s_1 and s_2 on frequency response is observed. The aspect ratio b/a affects the higher order modes while the lower modes can be tuned by dimensions of the slots.

3.1 Effect of Physical Parameters of the DR

3.1.1 *Effect of Breadth of the DR (a)*

The impedance bandwidth approximately remains unchanged while the AR can be tuned to find the wide CP bandwidth by varying a as depicted in Fig. 7. The variation in a significantly affects the higher order modes.

3.1.2 *Effect of Length of the DR (b)*

The increment in b brings the AR down over a wide span of frequency as shown in Fig. 8(b). Figure 8(c) shows that increment in b increases b/a, which brings the resonant modes closer. In Fig. 8(c), f_1, f_2, f_3 and f_4 are resonant frequencies of quasi modes TE^{y}_{111}, TE^{x}_{111}, TE^{y}_{221} and TE^{x}_{221}, respectively. The impedance bandwidth is not affected by the variation in *b*.

3.2 Effect of the Slot Lengths

3.2.1 *Symmetrical Stair Shaped Slot (s_1=s_2)*

Figure 9 shows the antenna response when $s_1/s_2 = 1$. The S_{11} response is unchanged for the different sets of s_1 and s_2. A wide AR bandwidth is obtained for $(s_1 + s_2)/l_s = 1.30$ as illustrated in Fig. 9(b). The decrement in $(s_1 + s_2)/l_s$ reduces

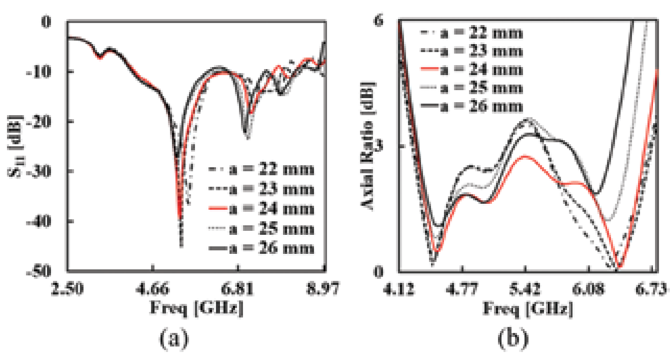

Figure 7. Effect of variation of breadth of the DR on (a) S_{11} and (b) AR response.

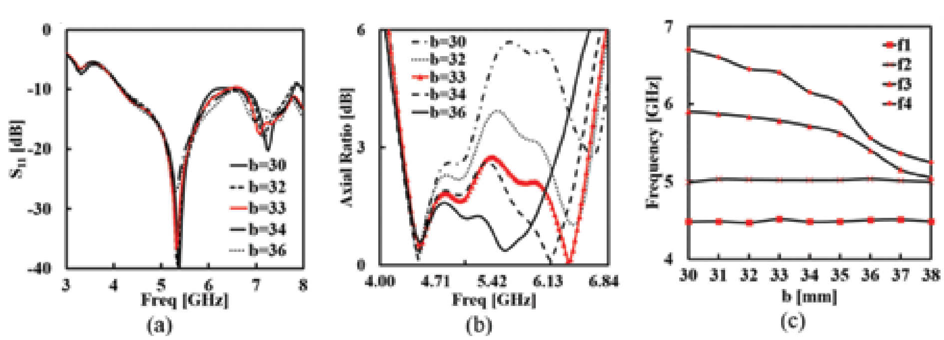

Figure 8. (a) S_{11}, (b) AR response of antenna and (c) resonant frequency of the modes with *b* as variable.

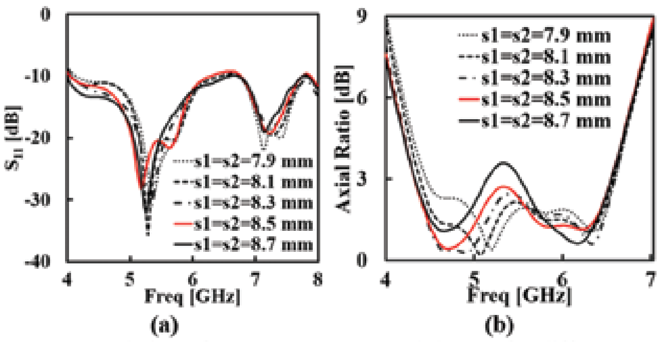

Figure 9. (a) S_{11} and (b) AR response for different sets of symmetrical side slots.

the separation between the minimas. Hence, AR bandwidth is reduced.

3.2.2 Asymmetrical Stair Shaped Slot ($s_1 \neq s_2$)

3.2.2.1 The Variation in s_1

It is observed in Fig. 10 that varying s_1 affects the second and third minima while first and fourth minima are stable. The AR can be tuned keeping impedance bandwidth unaffected.

3.2.2.2 The Sariation in s_2

Increasing s_2 mainly affects the lower two minima. For $s_2 = 7\ mm$, slot length ratios are $s_1/s_2 = 1.4428$ and $(s_1 + s_2)/l_s = 1.30$ for which a wide AR bandwidth is achieved. If $s_2 < 7\ mm$, s_1/s_2 doesn't fall in the defined range and thus AR bandwidth is reduced. The impedance bandwidth is unchanged as shown in Fig. 11.

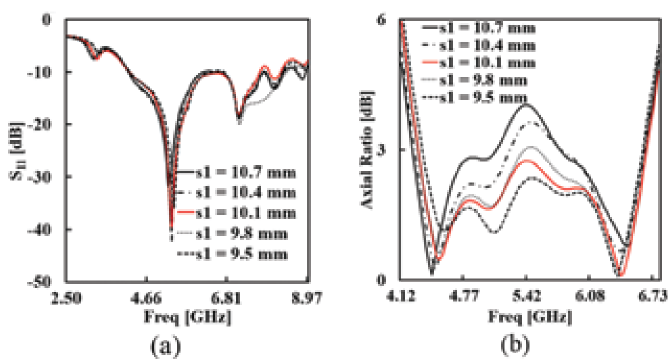

Figure 10. (a) S_{11} and (b) AR response with varible s_1.

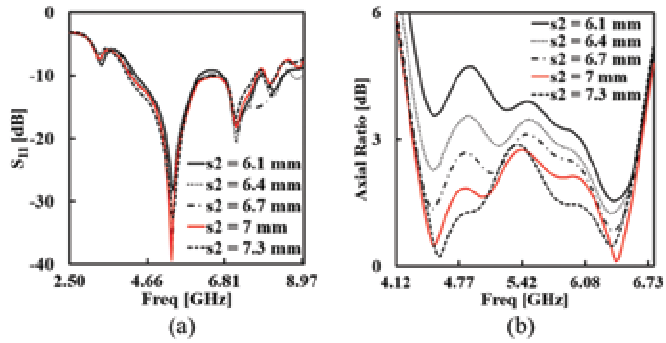

Figure 11. (a) S_{11} and (b) AR response with variable s_2.

4. MEASURED RESULTS AND DISCUSSION

The measured S_{11} response is depicted in Fig. 12. The antenna provides the simulated 60 per cent (4.18 GHz - 7.72 GHz) and measured 58.62 per cent (4.1 GHz - 7.5 GHz) impedance bandwidth. The simulated 3-dB AR bandwidth is 43.14 per cent (4.29 GHz - 6.65 GHz) and measured 40.89 per cent (4.26 GHz - 6.385 GHz). At 4.5 GHz, the antenna offers beamwidth of 209° and 106° in vertical principal planes. The far-field patterns are plotted in Fig. 13 showing that antenna provides the dominant RHCP field with a low cross-polarised component. The gain as shown in Fig. 14(a) varies within $0.5-3$ dBic in the CP passband with 80 per cent - 85 per cent radiation efficiency. Table 1 ensures the better performance of the proposed CPDRA in comparison to others.

Table 1. The performance comparison

Ref.	Method of finding CP response	ϵ_r	f_r (GHz)	BW_{AR} (%)	BW_{Im} (%)
5	Underlaid couplers	10	2.5	27.7	39.1
8	DR with slots	15	3.6	25	24.5
13	Cross slot	11	2.6	24.6	28.6
9	Trapezoidal DR	9.4	3.6	21.5	36.6
10	Diagonal inclined slits in DR	10	5.2	3.99	4.57
14	Spiral slot	12	2.13	25.5	-
Proposed	Stair-shaped slot	4.7	12.8	40.86	58.62

The symbols BW_{Im}, BW_{AR}, f_r represent impedance, AR bandwidth and resonant frequency, respectively

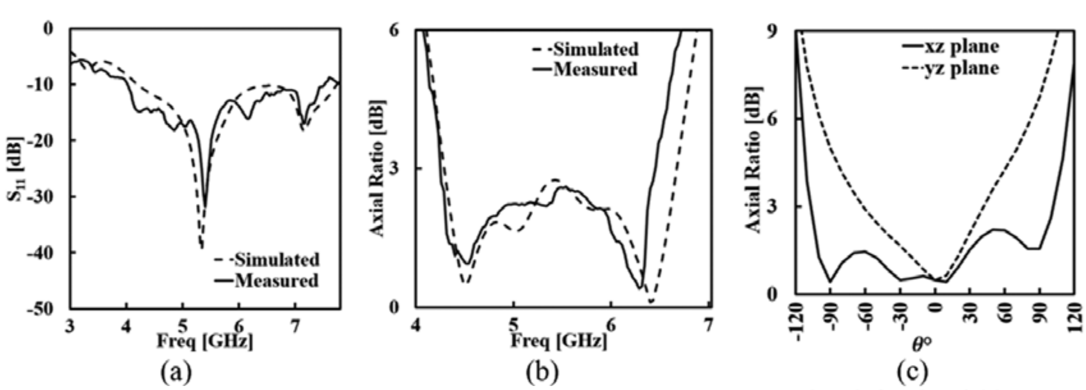

Figure 12. (a) S_{11}, (b) AR response and (c) AR variation with θ in the case of asymmetrical slot.

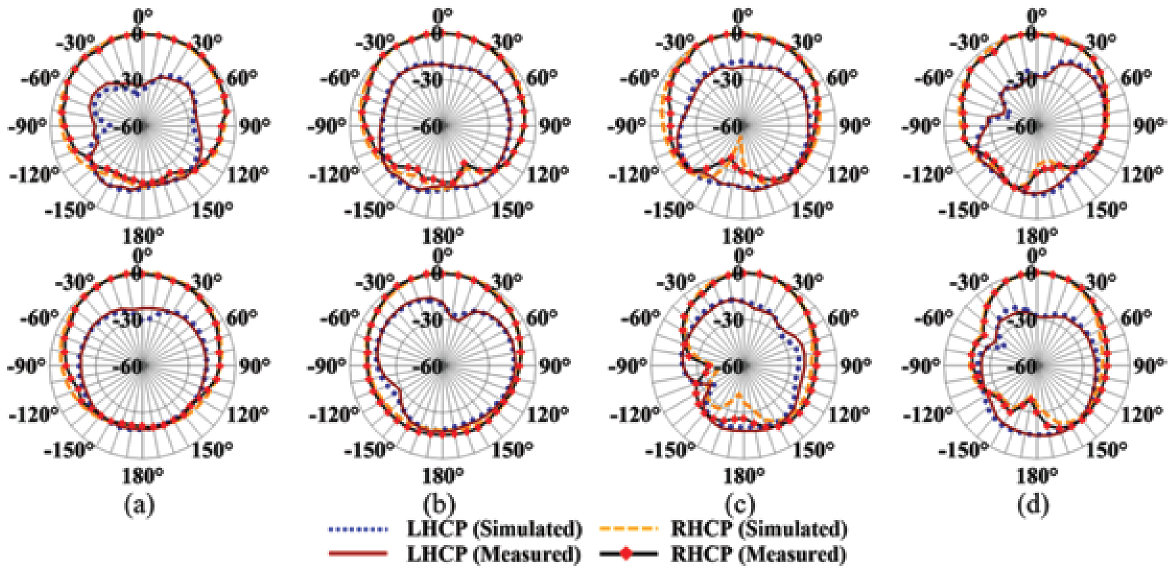

Figure 13. Radiation pattern at (a) 4.5, (b) 5, (c) 5.8 and (d) 6.3 GHz (the plots in first and second row are at $\phi = 0°$ and plane, respectively).

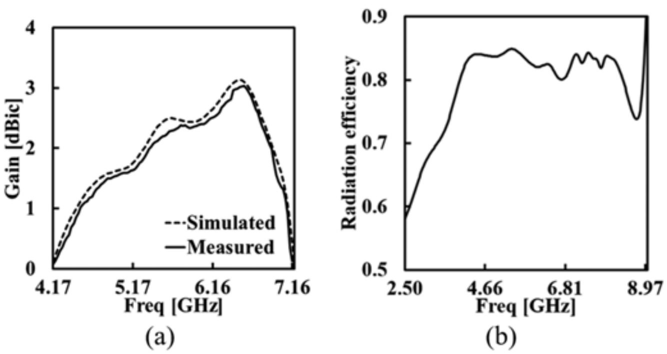

Figure 14. (a) The gain plot and (b) radiation efficiency.

5. CONCLUSION

A CPDRA with aperture coupled feeding technique through stair-shaped slot has been implemented. The criterion for selection of the dimension of the stair-shaped slot has been defined to obtain the wide CP bandwidth. The ranges of slot length ratios have been investigated. The antenna offers the impedance bandwidth of 58.62 per cent (4.1-7.5 GHz) and AR bandwidth of 40.86 per cent (4.26-6.385 GHz) for its utilisation in C-band applications. In addition, 3-dB AR beamwidth of 209° and 106° is achieved in $\phi = 0°$ and 90°-plane, respectively.

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