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Circularly Polarized Dielectric Resonator Antenna With Two Annular Vias

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ABSTRACT In this paper, a new technique for circular polarization in a slot coupled dielectric resonator antenna is proposed. The circular polarization is generated by inserting the two annular vias into dielectric resonator slightly off the diagonal position. In addition to the circular polarization, the proposed technique increases the total realized gain by 1.62 dB as compared to the via-less case on the account of increased directivity while maintaining the same aspect ratio of the DR. To validate the design, a prototype is fabricated and measured. The measured results show that the proposed circularly polarized dielectric resonator antenna has a -10 dB reflection bandwidth of 7.29% (3.3–3.55 GHz) and a 3 dB axial ratio bandwidth of 5.5% (3.28–3.465 GHz) with a measured RHCP gain of 6–7.1 dBic. The measured curves of the S_{11}, axial ratio, and the RHCP gain results are in good agreement with the simulated results.

INDEX TERMS Axial ratio, circular polarization, rectangular dielectric resonator antenna, right-handed circular polarization.

I. INTRODUCTION

A dielectric resonator antenna (DRA) is an antenna that consists of blocks of ceramic materials of various shapes. DRAs are mostly used at microwave and higher frequencies and make use of the radiating modes of a dielectric resonator (DR). In comparison with one- and two-dimensional planar antennas, a DR is more flexible and versatile due to the diversity of shapes and materials used. There are numerous advantages of a DRA, i.e., a small size, ease of excitation, and low loss, which make the DR a preferable choice for wireless communications [1] , [2]. On the other hand, certain applications such as global positioning systems, and satellite communication/navigation systems require low multipath interference and low polarization mismatch rates, making a circularly polarized (CP) antenna preferable to a linearly polarized (LP) antenna [3]–[6]. As a result, much attention has been paid to the design of CP DRAs over the past few decades [7]–[17].

Different techniques are available to realize circular polarization. A single-point feeding structure is the most promising among the available techniques to achieve compact dimensions. In on study [7], CP modes were generated using a stack of dielectric resonators, with each DR rotated at a certain angle. Orthogonal modes can also be excited by modifying the structure of the slots; i.e., V-shaped and Cross-shaped slots can be used to enable circular polarization [8], [9]. In another study [10], circular polarization is obtained by off-centered feeding of an annular slot. Different feeding structures are used to excite the orthogonal modes in the DR. A conformal spiral wire [11] was printed onto a hemispherical DR to excite orthogonal modes while a circular ring microstrip line with four open stubs [12] was used to excite TE_{11} mode in the DR. In additional work [13], [14], several parasitic elements were added to the DR to form a CP DRA. A parasitic strip was printed onto the top of a DR to realize circular polarization [13]. CP modes in DRA were excited with a parasitic strip placed at the corner [14]. CP can be generated by modifying the shape of the DR [15]–[17]. A cylindrical stair-shaped DRA devised by removing the block of the DR with an equal angular factor has been presented [15], whereas a spidron fractal DRA fed by a C-shaped slot to obtain a wideband CP band was realized [16]. A probe fed semi-eccentric annular DR, which is a semi-elliptical DR with a hollow elliptical cylinder [17], was shown to be able to generate circular polarization.

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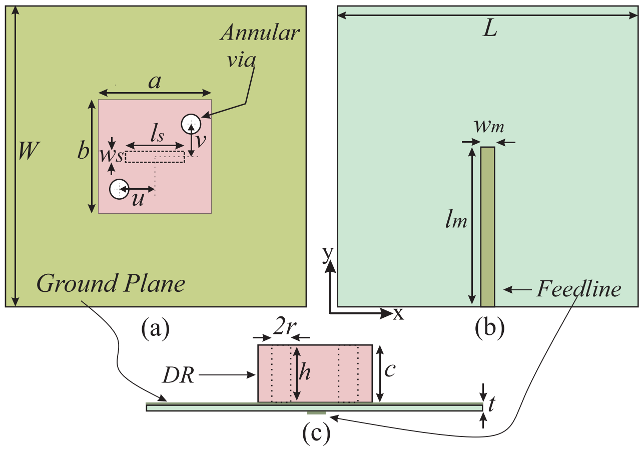

FIGURE 1. Geometry of the proposed design: (a) Top view. (b) Bottom view. (c) Side view. [$a = b = 30$, $c = 15$, $r = 2.5$, $u = 8.75$, $v = 5.8$, $l_s = 15.69$, $w_s = 2.89$, $w_m = 3.43$, $l_m = 47.39$, $t = 1.52$, $L = W = 90]_{mm}$.

In this article, a new technique that is based on a pair of annular vias is presented to realize the CP fields in the DRA. The idea to use the annular vias is developed from [18] where these were used to improve isolation between the MIMO DRAs by changing the fields in the DR. Thus, the CP fields were generated by inserting the annular vias into a DR with proper dimensions and the correct position with reference to the center of the DR. Moreover, it was found that the annular vias increase the total realized gain of the proposed structure by 1.62 dB as compared to its variants –with and without air-filled holes– on the account of increased directivity, thereby increasing the range of communication. The reflection coefficient, axial ratio (AR), RHCP gain, and radiation patterns were simulated using the ANSYS High-Frequency Structure Simulator (HFSS). The measurements were found to be in good agreement with the simulated results. The measured −10 dB reflection bandwidth and 3 dB axial ratio bandwidth (ARBW) of the designed DRA are 3.3–3.55 GHz and 3.28–3.465 GHz, respectively. The measured RHCP gain in the desired band varies from 6 to 7.1 dBic.

II. DESIGN OF THE PROPOSED DRA

The configuration of the proposed CP DRA is shown in Fig. 1. The proposed square DR has length a, height c, and dielectric constant 9.6 that is placed on the top layer of a Taconic RF−35 ($\epsilon_r = 3.5$, $\tan\delta = 0.0025$) with the dimensions of $l_g \times w_g \times h$. The DR is excited by a microstrip line coupled through a rectangular slot of length l_s and width w_s etched from the ground plane. The ground plane is printed on the top layer of the substrate and is in direct contact with the DR. Two annular vias of radius r and height h are inserted at a horizontal distance of u and vertical distance of v symmetrically with respect to the center of the DR but slightly off the diagonal such that they are grounded. A microstrip feed line of length l_m and width w_m is printed onto the bottom layer of the substrate. The DR is merely an LP that does not use annular vias. By incorporating two vias, CP fields are generated in the DR.

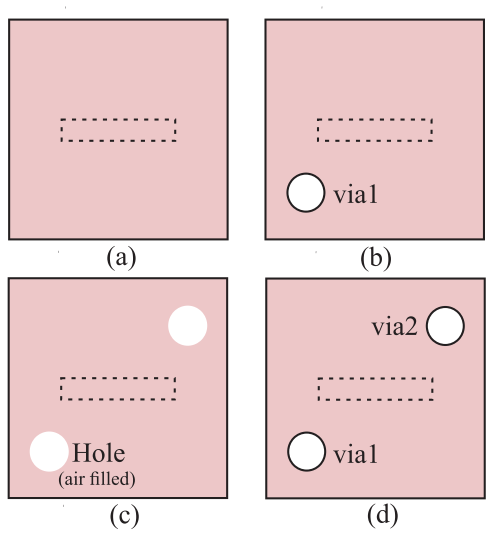

FIGURE 2. Configuration of antenna: (a) Ant1. (b) Ant2. (c) Ant3. (d) Ant4 (proposed antenna).

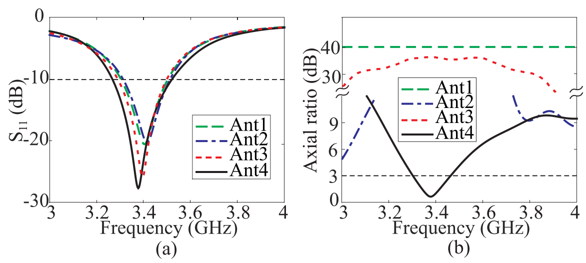

FIGURE 3. Comparison of Ant1, Ant2, Ant3, and Ant4: (a) Reflection coefficient. (b) Axial ratio along the *z-axis* ($\theta = 0°$, $\phi = 0°$) direction.

To confirm the performance of the proposed CP DRA, four designs, a DRA without vias (Ant1), a DRA with a single annular via1 (Ant2), a DRA with air-filled holes (Ant3), and the proposed structure: a DRA with two annular vias (Ant4), are investigated, as shown in Fig. 2. All designs are excited by microstrip-to-slot coupling with identical dimensions. The reflection coefficient and AR of these antennas are given in Fig. 3. It was found that the reflection bandwidths achieved by Ant1 to Ant3 are similar from 3.3–3.5 GHz with no overlapping 3 dB ARBW. Ant1 is well known to be linearly polarized. Ant2, which is designed with a single annular via1, the AR>3 dB resonances are observed around 3 GHz and 3.9 GHz. The performance will remain the same if Ant2 is simulated with only via2. In Ant3, the annular vias are replaced with air-filled holes, which results in linear polarization with AR>30 dB. Finally, when both vias, i.e., via1 and via2, are inserted simultaneously, termed Ant4, the reflection band is slightly increased, i.e., 3.27–3.54 GHz in addition to an overlapping 3 dB ARBW of 3.3–3.47 GHz. The simulated total realized gain, directivity, and radiation efficiency of Ant1, Ant3 and Ant4 are compared in Fig. 4. The radiation efficiency of 96% is the same for all designs, but the directivity of the proposed structure is higher than the other two structures by 1.63 dB. Fig. 5 shows the radiating modes in the DR with and without annular vias, clearly illustrating that quasi-TE^x_{113} is generated in all the cases. Thus, it is obvious

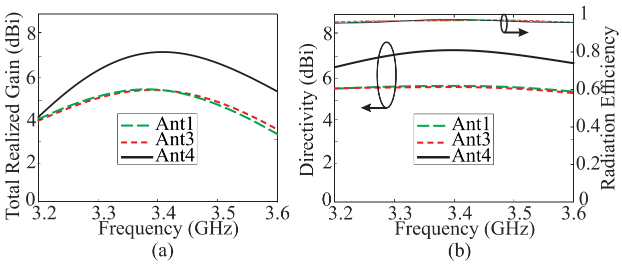

FIGURE 4. Comparison of Ant1, Ant2, Ant3, and Ant4: (a) Total Realized Gain. (b) Directivity and radiation efficiency.

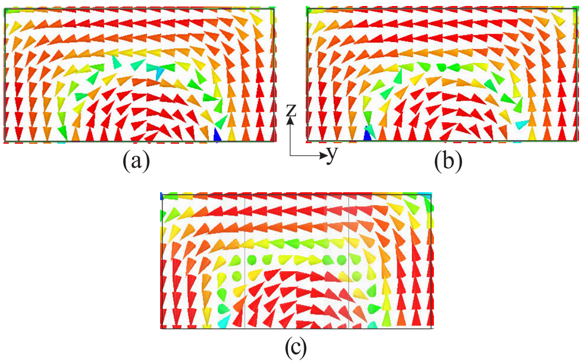

FIGURE 5. Current distribution of quasi-$TE^{x}{}_{113}$ mode: (a) Ant1. (b) Ant3. (c) Ant4(proposed antenna).

that with similar radiating modes and radiation efficiency, the annular vias increase the total realized gain for the same aspect ratio on the account of increased directivity.

To further elaborate this point, we designed and optimized a CP DRA using a conventional technique, i.e., with X-shaped slot coupling at the same frequency. Fig. 6 depicts the geometry of the conventional CP DRA. The comparison of simulated gain and AR of the conventional and proposed CP DRAs is plotted in Fig. 7. In case of the conventional CP DRA, the CP bandwidth and the CP gain of 4.35% and 6 dBic are achieved, respectively, which is comparable with the results in [19]. It can be concluded from Fig. 7 that the CP gain of the proposed structure is higher than the conventional CP DRA.

To assess the sense of circular polarization and the significance of the vias, the simulated current distribution on the top surface of the DR with the time-varying phase set to 3.36 GHz is assessed as shown in Fig. 8. It was noted that when the vias are inserted, the current distribution changes and CP fields are excited in the DR such that the current converges on one via but diverges from the second one at a time. As illustrated in Fig. 8(a), at time $t = 0$, all currents I_1, I_2, and I_3 are parallel that generate the total current I_R in the same direction, which is vertically downward in this case. As the phase changes to $t = T/4$ in Fig. 8(b), the currents on the vias are set up in such a way that the pairs I_1, I_2 and I_3, I_4 become orthogonal and the resultant I_R is aligned horizontally. The rotation of currents in the remaining half cycle can be explained similarly. Thus, the rotation of current is counter-clockwise when observed from the $+z$-axis. Therefore, the proposed CP DRA radiates right-handed circularly polarized (RHCP) waves.

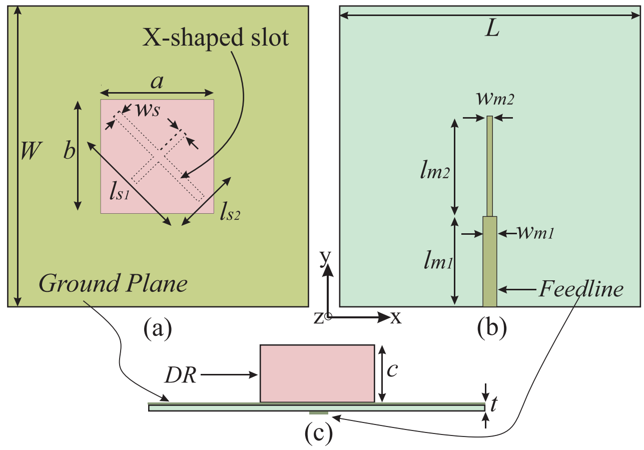

FIGURE 6. Geometry of the conventional CP DRA: (a) Top view. (b) Bottom view. (c) Side view. [$a = b = 28$, $c = 13$, $l_{s1} = 31$, $l_{s2} = 18$, $w_s = 2$, $w_{m1} = 3.43$, $w_{m2} = 1.6$, $l_{m1} = 23$, $l_{m1} = 26$, $t = 1.52$, $L = W = 76$]mm.

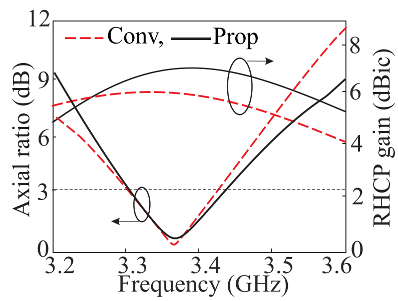

FIGURE 7. Comparison of the RHCP gain and axial ratio of proposed design with the conventional designs.

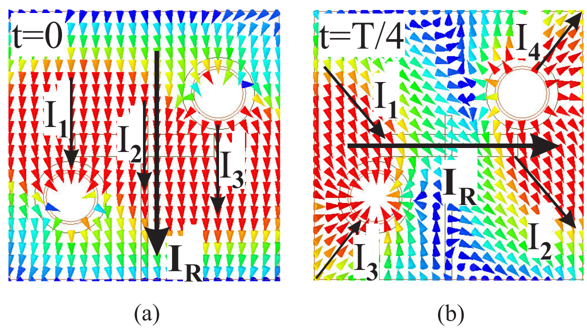

FIGURE 8. Simulated current distribution on top surface of DR: (a) $t = 0$. (b) $t = T/4$.

III. PARAMETRIC STUDY

To investigate the effects of different parameters, a parametric analysis is conducted. This study includes the variation in the radius r, height h, and horizontal u and vertical v positions of the vias with respect to the center of the slot. During the analysis, only one parameter can be modified at a time.

Fig. 9 shows the role of height h of the via. By decreasing h, both the reflection band and the 3 dB ARBW are shifted to higher frequencies. For vias with a height identical to that of the DR, a reflection band of 3.27–3.54 GHz and a 3 dB ARBW of 3.3–3.47 GHz are obtained. Fig. 9(b) also depicts the RHCP gain of the antenna with different values of h. It is clear that the RHCP gain increases as the height of the vias increases.

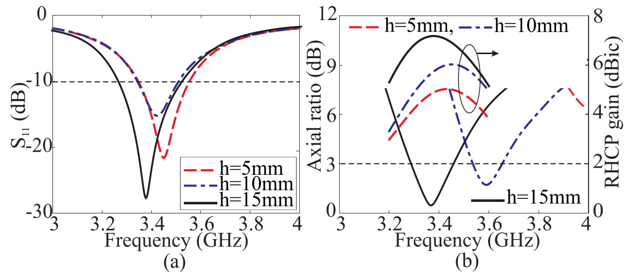

FIGURE 9. **Effect of variation in height of via: (a) Reflection coefficient. (b) Axial ratio and RHCP gain.**

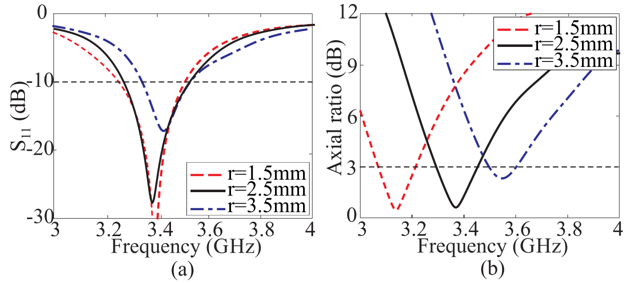

FIGURE 10. **Effect of variation in radius of via: (a) Reflection coefficient. (b) Axial ratio.**

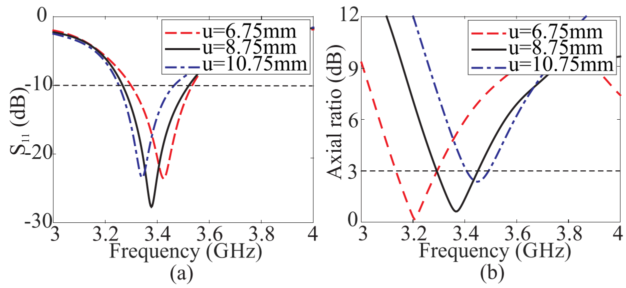

FIGURE 11. **Effect of variation in horizontal position of via: (a) Reflection coefficient. (b) Axial ratio.**

Fig. 10 shows the effect of the radius r of the vias. It is evident that when r decreases, there is not much of an effect on the reflection band, but the ARBW is shifted to a lower frequency. However, the resonance in both the reflection and AR bands shifts to a higher frequency as r increases. By optimizing r to some intermediate value, i.e., 2.5 mm, the -10 dB reflection band with overlapping 3 dB ARBW of 3.3–3.47 GHz is realized.

The effect of variation of the horizontal position u is illustrated in Fig. 11. It was noted that when u decreases, the DR resonates at higher frequencies while the AR shifts to a lower frequency. However, by increasing u, the resonance in the reflection band moves to a lower frequency while the AR is realized at higher frequencies with poorer performance. However, for $u = 8.75$ mm, the optimum performance is achieved. Similar behaviour can be seen in Fig. 12 with variation of the vertical position of via v in the reflection band. On the other hand, the AR resonance frequency remains on the same band with poor performance. As the vias are positioned closer to or farther away from the slot, the tuning is disturbed. The optimum value of $v = 2.79$ mm is selected for the required results.

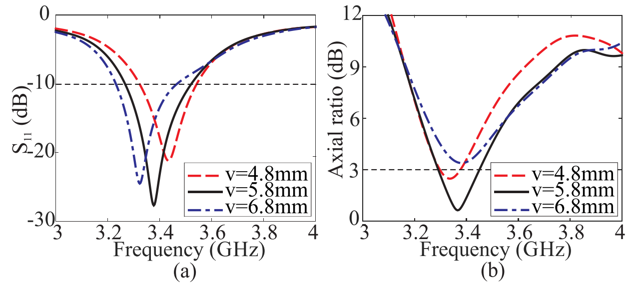

FIGURE 12. **Effect of variation in vertical position of via: (a) Reflection coefficient. (b) Axial ratio.**

Concluding the overall parametric study, it is obvious that the ARBW is more vulnerable to any changes in parameters than the reflection band.

IV. MEASURED RESULTS

After obtaining the optimum results of the designed parameters, a prototype of the CP DRA is fabricated, as depicted in Fig. 13. For ease in fabrication, the bottom metal is shorted to the ground plane through the vias. Annular vias in the DR were realized using copper tape and are shorted to the bottom metal. Subsequently, Nylon bolts were inserted through the annular vias, with a firm attachment realized with Nylon nuts so that the air gap is removed between the DR and the ground. The reflection coefficients of a prototype were measured using Agilent E5071B RF network analyzer. The simulated and measured results for the reflection coefficient are depicted in Fig. 13(a). The antenna attains the simulated and measured -10 dB reflection band of 3.27–3.54 GHz and 3.3–3.55 GHz, respectively. The simulated and measured results of the proposed design for both the AR and RHCP gain in the boresight direction ($\theta = 0$) are shown in Fig. 14(b). The simulated 3 dB AR bandwidth corresponds to 3.3–3.47 GHz, while the measured result is 3.28–3.465 GHz. It is important to note that the total AR band lies within the reflection band. Therefore, the overall AR bandwidth can be utilized for CP applications. The variation in the measured RHCP gain of the proposed antenna is 6–7.1 dBic within the AR bandwidth. The difference between the measured and simulated RHCP gain varies from 0.1 to 0.3 dB. For some applications, the antenna has AR$<$3 dB at one angular location is not enough because the signal does not necessarily arrive through one angular direction. Thus, antenna should have a wider 3 dB AR beamwidth. Fig.15 compares the simulated and measured AR beamwidths in both planes. The simulated and measured 3 dB beamwidths in the xz–plane are 68°(from $-34°$ to $+34°$) and 71°(from $-37°$ to $+34°$), respectively, while in the yz–plane the beamwidths are 107°(from $-51°$ to $+56°$) and 115°(from $-57°$ to $+58°$), respectively. These figures demonstrate that the measured and simulated results are in good agreement, apart from certain discrepancies which can be attributed to fabrication tolerances.

The measured and simulated radiation patterns of the proposed antenna on both planes are shown in Fig. 16 at 3.36 GHz. It is clear from the figure that the measured and

TABLE 1. Comparison of the proposed single-feed CP generation technique with the earlier ones.

Ref	Technique	−10 dB IBW(%)	3 dB AR(%)	CP Gain(dBic)	Merits/Demerits
[7]	Stacked DR with rotation angle	21.21	5	6.4	Complexity
[10]	Off-centered feeding	5.8	3.47	2.7	Simple
[11]	Conformal spiral wire feeding	12.03	3.9	-	Complexity
[12]	Circular ring with four micro-stirp lines feeding	8	2.92	8.6	Extra feed footprint
[15]	Cylindrical stair shaped	51.21	8.01	5	Complexity
Prop.	Annular vias in DR	7.29	5.5	7.1	Simple and compact

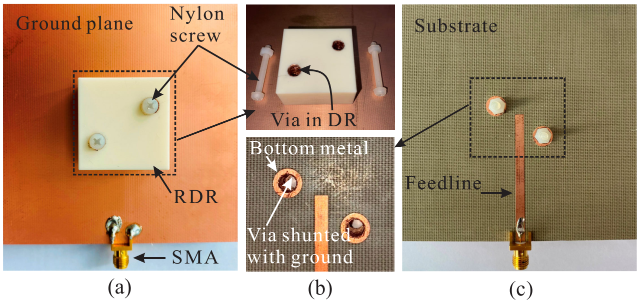

FIGURE 13. Photograph of the proposed design: (a) Top view. (b) Top and bottom view with open screw. (c) Bottom view.

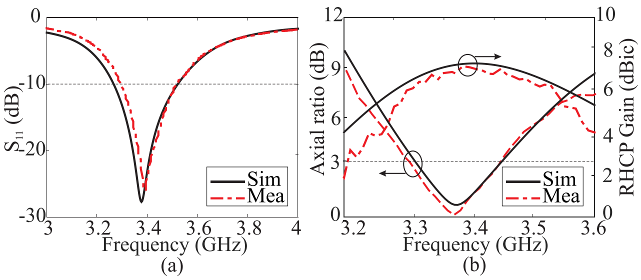

FIGURE 14. Simulated and measured results: (a) Reflection coefficient. (b) AR and RHCP gain.

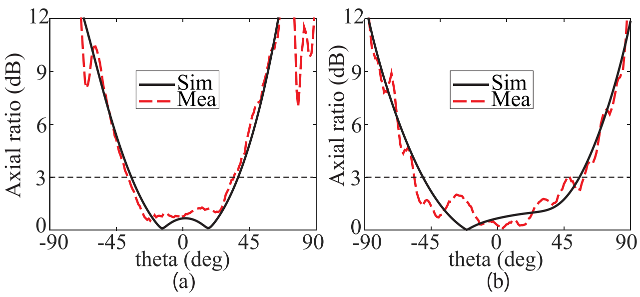

FIGURE 15. Simulated and measured AR beamwidths at 3.36 GHz: (a) *xz*−plane. (b) *yz*−plane.

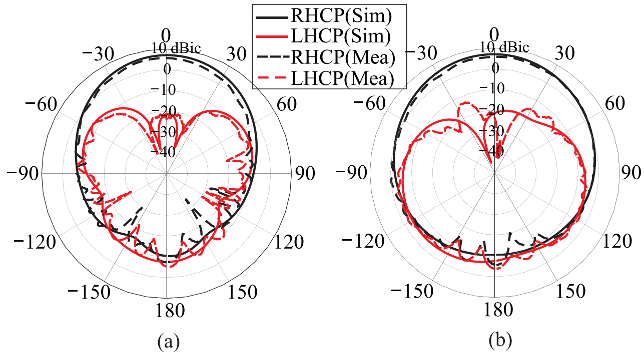

FIGURE 16. Simulated and measured radiation patterns at 3.36 GHz: (a) *xz*−plane. (b) *yz*−plane.

simulated results are in good agreement. In both cases, the measured RHCP is stronger than the LHCP by 30 and 31 dB, respectively. Table 1 summarizes the comparison of the proposed technique with earlier studies in terms of IBW, ARBW, maximum CP gain, and merits and demerits.

In [7], four DR samples are stacked and rotated at a specific angle that achieves a wider −10 dB IBW than the proposed design due to the lowering of the effective dielectric constant. However, the CP gain and 3 dB ARBW are smaller and the geometry is complex as compared to the proposed design. The off-centered feeding technique is employed for circular polarization in [10]. Although, the design is simple, but possesses a narrower −10 dB IBW and 3 dB ARBW along with lower CP gain as compared to the proposed design. In another study [11], a spiral feeding structure is printed on a hemispherical DR to achieve circular polarization, necessitating high precision printing due to complex feeding structure on the curvature of the DR. Moreover, this design results in a narrower 3 dB ARBW of 3.9%. Circular polarization is achieved by employing a feeding technique that consists of a circular microstrip line with four open stubs in [12]. The design has a large feed footprint, comparable −10 dB IBW, and a narrow 3 dB ARBW of 2.92%, but a higher CP gain of 8.6 dBic than the proposed design. In [15], a complex cylindrical stair shape of the DR is adapted that obtains a wider −10 dB IBW and 3 dB ARBW and lower CP gain as compared to the proposed design. Moreover, unlike the geometries in [7], [10]–[12], and [15], the proposed structure is simple, compact, and uses Nylon screws to hold the DR firmly to the ground, thereby making it resistant to flickering.

V. CONCLUSION

In this letter, a slot-coupled CP DRA has been presented and studied. Vertical annular vias were inserted into a DR, and CP modes were generated. The effect of the height of the vias on the CP gain of the antenna was investigated, showing that vias cause an increase in the gain. The measured reflection band ($S_{11} < -10$ dB) and ARBW (AR<3 dB) of the designed DRA are 7.29% (3.3–3.55 GHz) and 5.5% (3.28–3.465 GHz), respectively, with a higher CP gain varies between 6–7.1 dBic. Moreover, the antenna has wider measured 3 dB beamwidths of 71°(from −37° to +34°) and 115°(from −57° to +58°) in the *xz*–plane and *yz*–plane, respectively. Good agreement is found between the simulated and measured results. The design is a good candidate for WiMAX applications. It is also important to note that the design can be scaled to any desired frequency.

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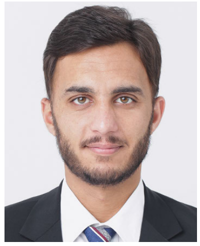

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