IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received April 22, 2019, accepted May 15, 2019, date of publication May 20, 2019, date of current version June 4, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2917702

Singly-Fed Rectangular Dielectric Resonator Antenna With a Wide Circular Polarization Bandwidth and Beamwidth for WiMAX/Satellite Applications

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ABSTRACT A rectangular dielectric resonator antenna (DRA) has been excited using a unique conformal H-shaped metal strip. Using this excitation, the degenerate mode pair of first higher order $\mathrm{TE}^{\mathbf{x}}_{\boldsymbol{\delta}\mathbf{13}}$ and $\mathrm{TE}^{\mathbf{y}}_{\mathbf{1}\delta\mathbf{3}}$ has been excited for bandwidth improvement and high gain. A broadband circular polarization (CP) over a bandwidth of ∼20% (3.67–4.4 GHz) in conjunction with a wide impedance-matching bandwidth of ∼27.7% (3.67–4.73 GHz) has been achieved. A CP beamwidth of ∼89° has been offered by the antenna in $\Phi = 0°$ plane and ∼32° in $\Phi = 90°$ plane. A high gain of ∼6.8 dBic has been provided by the antenna, which is a significant improvement to those circularly polarized rectangular DRAs reported in the literature for similar applications. This broad CP bandwidth and beamwidth can be considerably beneficial for the worldwide interoperability for microwave access (WiMAX) and satellite applications. Furthermore, the proposed antenna has been fabricated to validate the simulated results. The measured results have been observed to agree well with the simulated results.

INDEX TERMS Dielectric resonator antenna, circular polarization, wide-band antenna, H-shaped antenna, WiMAX, satellite communication.

I. INTRODUCTION

From the last few decades, DRAs have been focused by wireless communication researchers for high-frequency applications because these antennas exhibit very useful features such as high radiation efficiency, wide bandwidths, small sizes, different shapes, flexible excitation techniques, and achieving variety of radiation characteristics by excitation of different modes [1]–[5]. The resonant frequency of the DRA mainly depends on the different parameters of the dielectric resonator used, such as size, shape, and dielectric permittivity. According to shapes, the rectangular DRA is more preferred over cylindrical and hemispherical DRAs due to the flexibility in selecting the appropriate aspect ratio. Therefore, the antenna researchers are very interested to use rectangular DRAs. Also, it is easy to achieve the anticipated profile and impedance bandwidth characteristics for rectangular DRAs [6]. The DRAs are also better in terms of higher radiation efficiency due to absence of surface wave and wider band-width as compared to microstrip antenna [7].

Recently circularly polarized DRAs have acquired much more attention as compared to linearly polarized DRAs [8]–[20]. This is because a circularly polarized antenna is a potential solution for multipath and fading problems. Furthermore, the circularly polarized systems are considerably less sensitive to the orientation of transmitting and receiving antennas that is very important for many applications such as WiMAX technology, global positioning systems, and satellite communications [19], [21].

The associate editor coordinating the review of this manuscript and approving it for publication was Mohsen Khalily.

Additionally, the circularly polarized DRAs can be designed using a dual-feeding mechanism. However, this approach has two major limitations: its large size and the complexity of the feeing network [8]–[10].The singly fed DRAs are very popular because of their compact sizes and simple geometries [11]–[20]. By the increasing demands of wireless communication, researchers are working hard to achieve wideband circular polarization. But to achieving wideband CP by using simple rectangular DR is challenging. However, efforts to modify the shapes of DRs increase costs. Also, extra time and work is needed in the design stage to process ceramic materials. Since DRAs are made up of ceramics materials which are very hard so cutting and drilling is always a complex job. Further, use of multiple DRs in a single antenna or use of metallic walls add complexity and overall size of antenna is increased [22]–[24]. Hence, a single feeding scheme using a DR with a conventional shape is much more desirable [16]–[20].

Few circularly polarized rectangular DRAs operating in WiMAX frequency range has been reported in literature for instance: a rectangular DRA excited by the conformal strip has been reported in [16]; here, a CP bandwidth of 2.7% has been achieved using a parasitic patch and a useful gain of 4 dBic has been provided. In [17], the authors reported a circularly polarized rectangular DRA excited by concentric open concentric half-loops metallic strips. A broadband CP of 14% along with a gain of 5 dBic has been achieved. A circularly polarized rectangular DRA excited by a stair shaped microstrip line along with a pair of L-shaped slots in the ground has been reported in [18]. The proposed configuration offered a 3-dB axial ratio (AR) bandwidth of 17.59% with a useful gain of 3.86 dBic. A CP bandwidth of 20.62% has been provided by a cubic DRA energized by a question mark-shaped microstrip feed and a gain of 1.1 dBic has been reported [19]. Further, a rectangular DRA has been excited using triangular ring-shaped aperture along with microstrip line and parasitic patch to generate CP. The antenna offered a CP bandwidth of 2.29% and a gain of 5 dBic as reported in [20].

In all discussed literature, a good impedance-matching bandwidth has been achieved over the same frequency range. All the discussed antennas have been excited in the fundamental mode TE_{111}, achieved CP band can be utilized for WiMAX (3.3-3.7 GHz) applications.

In this study, a novel low cost H-shaped conformal metal feeding strip has been proposed to excite the rectangular DRA. Using this excitation, a broadband CP has been achieved without any multi layering or any complicated cutting of the DRA. The degenerate mode pair $TE^{x}_{\delta 13}$ and $TE^{y}_{1\delta 3}$ has been excited to generate wide CP bandwidth. The DRA has been excited in higher order mode for high gain applications [14]. The return losses, AR, beamwidth, radiation patters, and gain have been simulated and measured. The simulated results correlated well with the measured results. The proposed antenna provides broadband CP along with wide beamwidth which make it useful in different wireless applications such as WiMAX technologies [19] and satellite communication [21].

The antenna geometry has been provided in Section II, the antenna optimization has been explained in Section III, and the comparison between simulated and measured results of the proposed antenna have been discussed in Section IV. In Section V, the conclusion has been drawn.

II. ANTENNA GEOMETRY

A novel H-shaped monopole has been proposed to excite the rectangular DRA as illustrated in Figure 1. The antenna has been designed in CST® Microwave Studio 2017 using the finite-integration technique in the time-domain [25]. The optimized dimensions of the rectangular dielectric block are, a = 26.1 mm, b = 25.4 mm, and c = 14.3 mm.

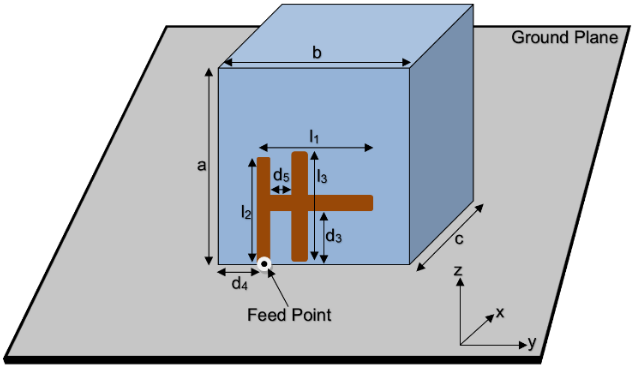


FIGURE 1. Rectangular DRA fed by H-shaped conformal metal strip.

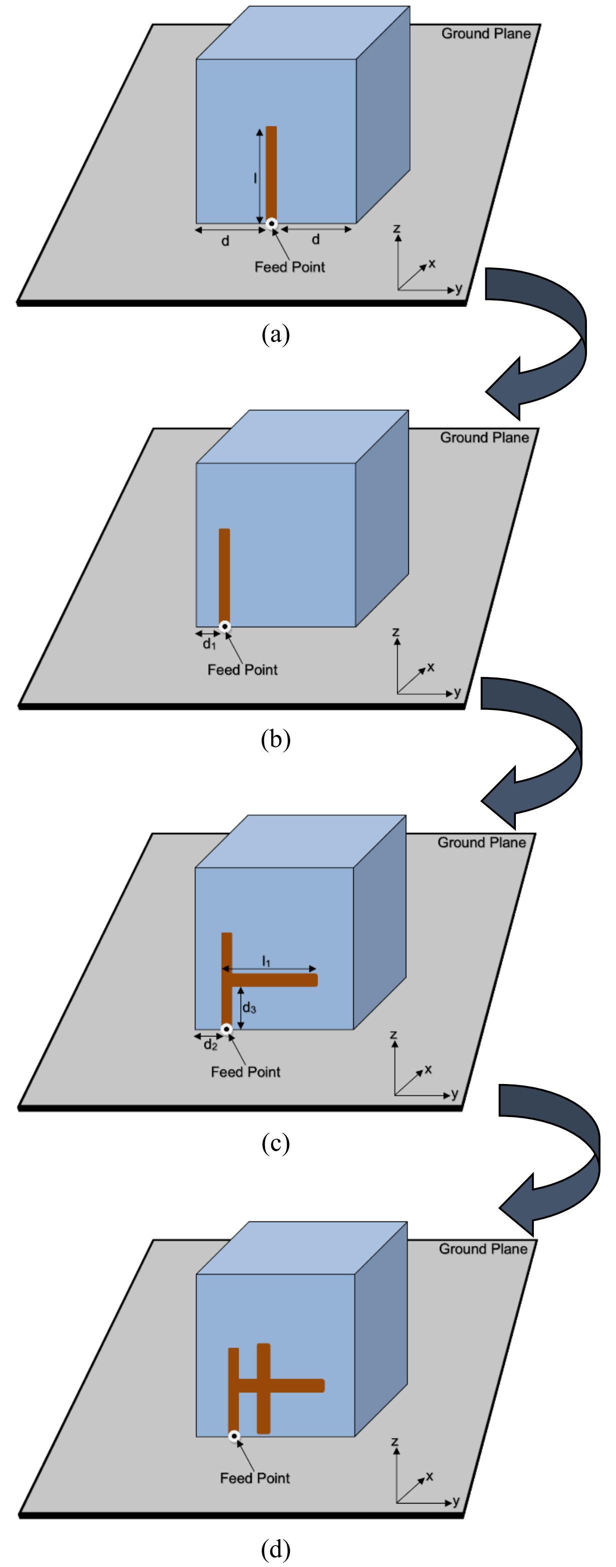
The rectangular DRA with permittivity, $\epsilon_r = 10$ has been modeled using the hexahedral meshing by setting 35 cells per wavelength. Similarly the 20 cells per max model box edge have been used to mesh the design. And 20 has been set as the fraction of maximum cell near to model, which provided a total of 594,048 unknowns. The H-shaped feeding strip has been proposed after numerous modifications. The shape and position of the feeding strip has been optimized using iterative design procedure to excite the degenerate mode pair for circularly polarized wave generation. The H-shaped conformal metal strip comprises of three individual strips. The lengths and widths excitation strip have been optimized by running several simulations using different parameter sweeps.

III. ANTENNA OPTIMIZATION

The final design has been proposed after considering four design configurations as presented in Figure 2. The proposed configuration has been selected on the basis of improved bandwidths and high gain.

A. CONFIGURATION 1

Configuration 1 has been designed by placing the single conformal strip at the center of the DRA surface as presented in Figure 2 (a). The optimized feed parameters are $d = 12.2$ mm and $l = 11$ mm. The width of the feeding strip is 1 mm. Using this excitation mechanism, the



(a)

(b)

(c)

(d)

FIGURE 2. **Methodology adopted to design proposed circularly polarized antenna. (a) Configuration 1. (b) Configuration 2. (c) Configuration 3. (d) Proposed configuration.**

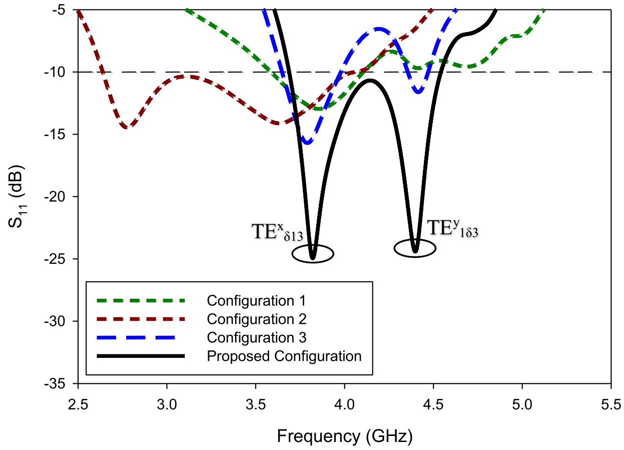


FIGURE 3. **Comparison of the return losses.**

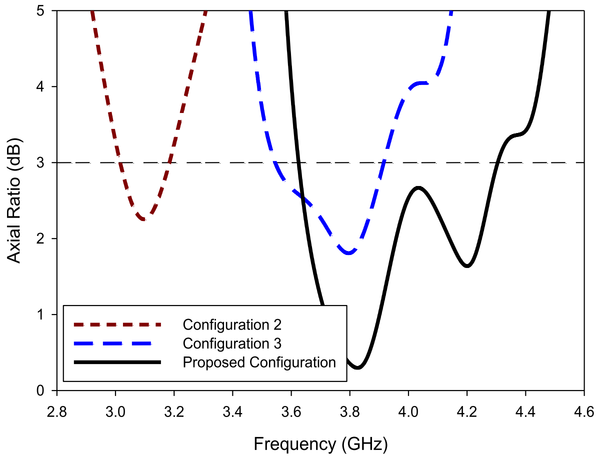


FIGURE 4. **Comparison of the axial ratios.**

rectangular DRA has been excited in its fundamental mode $TE^y_{1\delta 1}$ at 3.85 GHz as presented in Figure 6. The antenna is linearly polarized because degenerate mode pair has not been excited. An impedance-matching bandwidth ($|S_{11}| \leq 10$ dB) of ~17% has been offered by the antenna as depicted in Figure 3. The axial ratio and gain for this configuration has not been shown in Figure 4 and Figure 5 respectively because the antenna is linearly polarized.

B. CONFIGURATION 2

Configuration 2 is a modification of configuration 1. This configuration has been obtained by changing the feeding strip position. All other parameters remain constant as shown in Figure 2 (b). Using this off-set position, the orthogonal degenerate mode pair has been excited; that is responsible for CP wave generation [26]. Further, the degenerate $TE^x_{\delta 11}$ at 2.771 GHz and $TE^y_{1\delta 1}$ at 3.635 GHz has been excited as shown in Figure 7. The optimized strip position is observed to be at $d_1 = d - 0.75\lambda$, that is, $d_1 = 4$ mm. Using this excitation position the AR bandwidth of ~5.3% in conjunction with S_{11} bandwidth of ~50% over same frequency range have been achieved by the antenna as presented in Figure 4 and Figure 3 respectively. A useful gain of ~5.29 dBic has been provided by the antenna along the whole CP bandwidth as

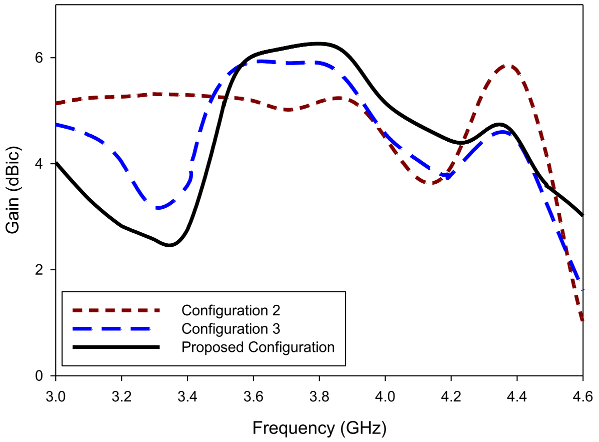


FIGURE 5. Comparison of the gains.

demonstrated in Figure 5. The achieved CP bandwidth is not enough for targeted applications, so design is need to be modified further.

C. CONFIGURATION 3

Configuration 3 has been constructed by further modifying configuration 2 to enhance CP bandwidth and gain as shown in Figure 2 (c). The modifications involve addition of second strip to the conformal feeding strip. The optimized feed parameter are $l_1 = 11$ mm with a width of 1.5 mm and $d_2 = 5$ mm, and $d_3 = 5$. Using this configuration the degenerate mode pair of first higher-order $\mathrm{TE}^{x}_{\delta 13}$ at 3.79 GHz and $\mathrm{TE}^{y}_{1\delta 3}$ at 4.41 GHz has been excited as presented in Figure 8. As shown $\mathrm{TE}^{y}_{1\delta 3}$ is not much clear at 4.41 GHz, this because impedance-matching is not good enough. As depicted in Figure 3, the $|S_{11}| \leq 10$ dB bandwidth of $\sim$8.9% has been provided by the antenna because majority of the return loss is greater than -10 dB; this is further optimized by the design modifications in the proposed antenna. The 3-dB axial ratio bandwidth of 9.5% has been achieved as shown in Figure 4. A successful overlapped CP bandwidth of $\sim$7.2% has been attained by the antenna. A useful gain of $\sim$5.89 dBic has been achieved along the whole CP bandwidth as demonstrated in Figure 5. As observed, configuration 3 performs better than configuration 2 in terms of the CP bandwidth and gain. However, the antenna needs to be modified further for enhancing the CP bandwidth. The impedance-matching bandwidth and gain also need to be improved.

D. PROPOSED CONFIGURATION

The proposed antenna has been designed by adding a third length in the feeding strip to make it an H-shaped conformal strip as illustrated in Figure 2 (d). The size of the feeding strip has been optimized by iterative design procedure opted by parametric study as shown in Figure 10, 11, and 12. The optimized feed parameters are $l_2 = 10$ mm, $l_3 = 10.5$ mm and $d_4 = 6$ mm $d_5 = 1$ mm. The width of l_3 is 1.5 mm. Design modifications have been made for further tuning, bandwidth enhancement and gain improvement. A wide impedance-matching bandwidth of $\sim$23% has been achieved as depicted in Figure 3. The degenerate mode pair, $\mathrm{TE}^{x}_{\delta 13}$ at 3.82 GHz and $\mathrm{TE}^{y}_{1\delta 3}$ at 4.4 GHz has been excited as shown in Figure 9. The orthogonal mode pair is quite clear at specific frequencies because of improved impedance-matching bandwidth. A broad CP bandwidth of $\sim$17% along with a high gain of $\sim$6.3 dBic has been provided by the proposed antenna as shown in Figure 4 and Figure 5 respectively.

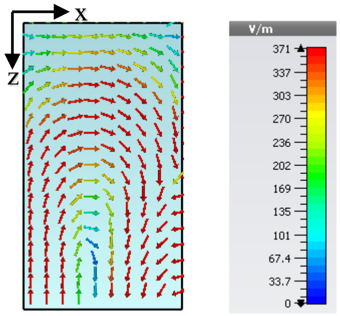
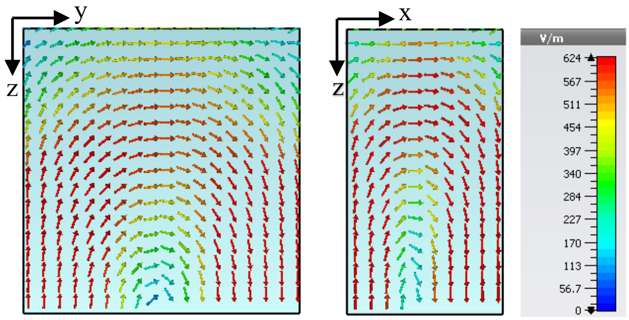
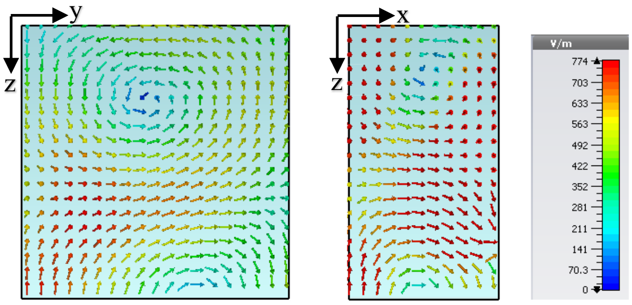


FIGURE 6. E-field distribution of the configuration 1 $\mathrm{TE}^{y}_{1\delta 1}$ at 3.85 GHz.



(a) (b)

FIGURE 7. E-field distribution of the configuration 2 (a) $\mathrm{TE}^{x}_{\delta 11}$ at 2.771 GHz and (b) $\mathrm{TE}^{y}_{1\delta 1}$ at 3.635 GHz.

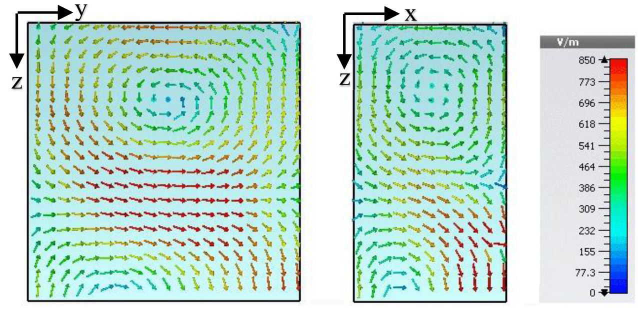


(a) (b)

FIGURE 8. E-field distribution of the configuration 3 (a) $\mathrm{TE}^{x}_{\delta 13}$ at 3.79 GHz and (b) $\mathrm{TE}^{y}_{1\delta 3}$ at 4.41 GHz.

IV. RESULTS AND DISCUSSION

The prototype on the proposed antenna shown in Figure 13 has been built using the ECCOSTOCK HiK with



(a) (b)

FIGURE 9. E-field distribution of the proposed configuration (a) $TE^{x}_{\delta 13}$ at 3.82 GHz and (b) $TE^{y}_{1\delta 3}$ at 4.4 GHz.

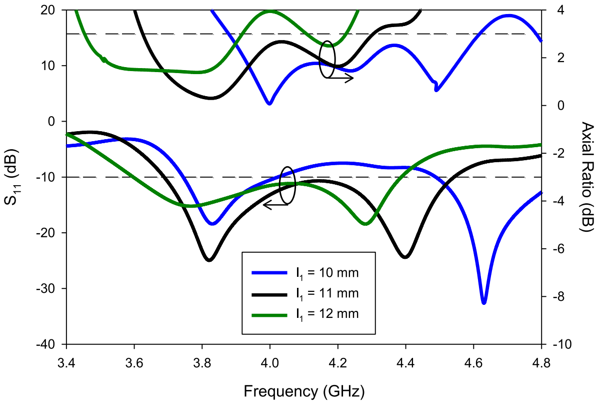


FIGURE 10. Return losses and axial ratio bandwidths of the rectangular DRA with various lengths of l_1.

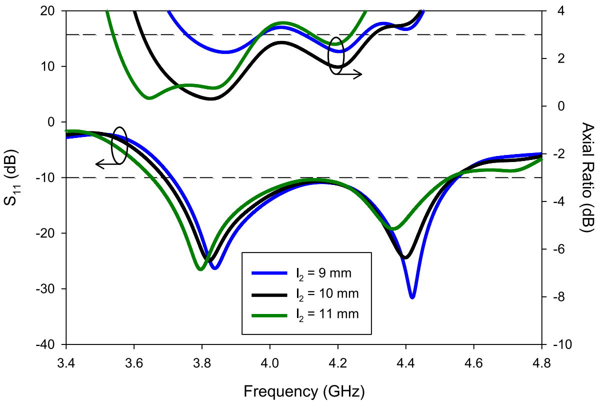


FIGURE 11. Return losses and axial ratio bandwidths of the rectangular DRA with various lengths of l_2.

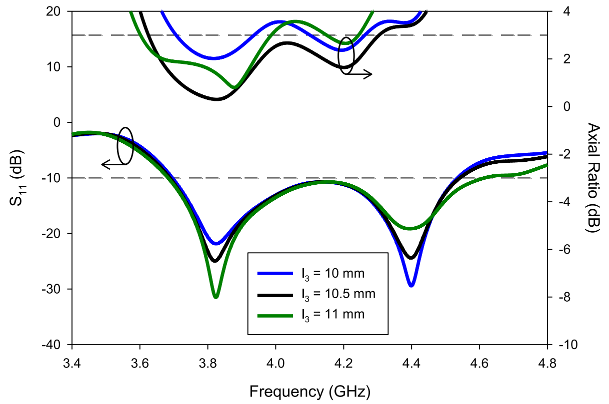


FIGURE 12. Return losses and axial ratio bandwidths of the rectangular DRA with various lengths of l_3.

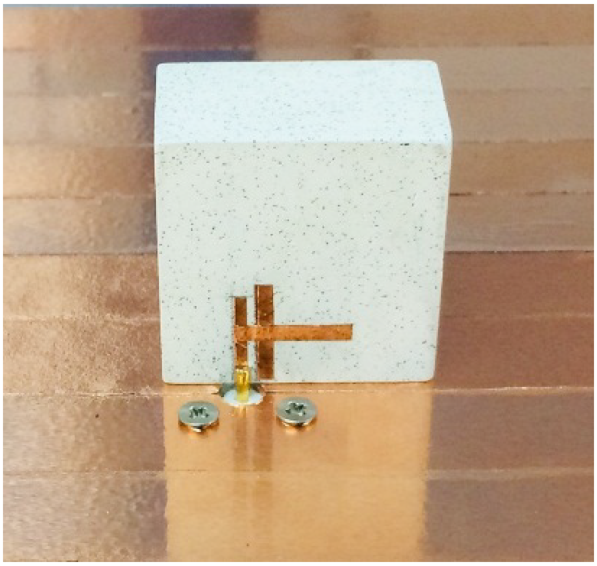


FIGURE 13. Prototype of the rectangular DRA fed by the H-shaped conformal metal strip.

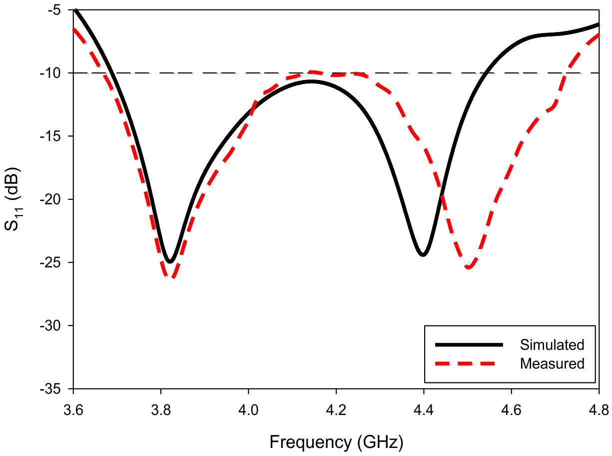


FIGURE 14. Return losses of the rectangular DRA fed by the H-shaped conformal metal strip.

permittivity, $\epsilon_r = 10$ and loss tangent (δ) of 0.002. The H-shaped strip has been cut from adhesive-backed copper tape to stick easily on DRA surface. An aluminum ground plane of 350 × 350 mm^2 has been employed. A vector network analyzer N5234A has been used for near field measurements. Far field measurements have been made using an antenna far field anechoic chamber. An SMA connector has been soldered to the edge of the feeding strip at the feed point. A 50-Ω coaxial cable has been used to connect SMA to the network analyzer for measurements. The DRA has been attached to a double-sided adhesive conducting copper tape,

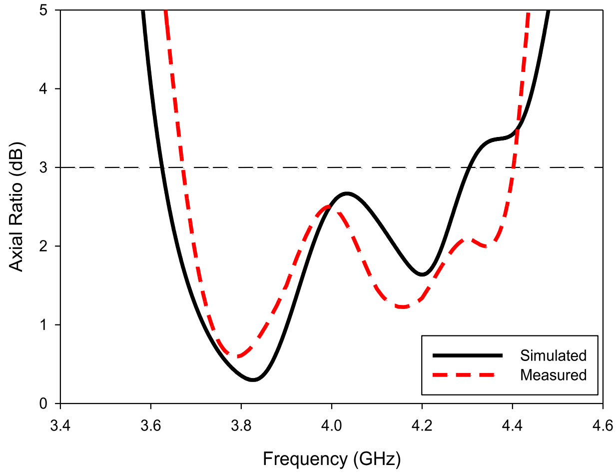


FIGURE 15. Axial ratio of the rectangular DRA fed by the H-shaped conformal metal strip.

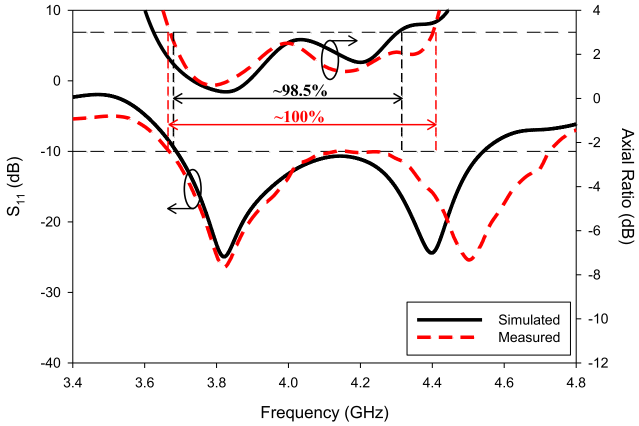


FIGURE 16. Region of overlapping bandwidths for return losses and axial ratio of the rectangular DRA fed by the H-shaped conformal metal strip.

which is placed on ground plane to remove the possible air gap as reported in [27].

The resonant mode frequencies of the rectangular DRA can be predicted using mathematical equations described in dielectric waveguide model (DWM) [29]. The estimated mode frequencies by DWM are $\mathrm{TE}^{x}_{\delta 13}$ at 3.89 GHz and $\mathrm{TE}^{y}_{1\delta 3}$ at 4.53 GHz. The comparison between the simulated and measured return losses has been presented in Figure 14. The $\mathrm{TE}^{x}_{\delta 13}$ has been measured and simulated at 3.82 GHz. Whereas, $\mathrm{TE}^{y}_{1\delta 3}$ has been measured at 4.5 GHz as compared to 4.4 GHz in the simulation. The mode frequencies predicted by DWM, computed by simulation, and measured by fabrication show a close resemblance. As observed $|S_{11}| \leq 10$ dB has been achieved over a wide bandwidth of ~27.7%. Marginal difference has been observed between theory and measurements caused by the experimental imperfections and fabrication errors.

In Figure 15 the simulated and measured axial ratio in broadside direction (i.e. $\theta = 0°, \Phi = 0°$) provided by the antenna has been illustrated. As demonstrated the measured axial ratio bandwidth below 3-dB extends from 3.67–4.4 GHz, that is, ~20%. Furthermore, the minimum value of the 3-dB AR computed in simulation is 0.29 dB at

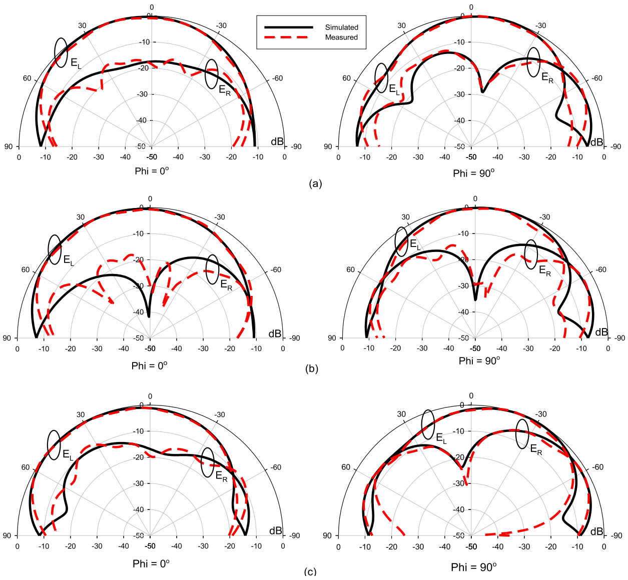


FIGURE 17. Radiation patterns of the rectangular DRA fed by the H-shaped conformal metal strip. (a) 3.67 GHz. (b) 3.8 GHz. (c) 4.23 GHz.

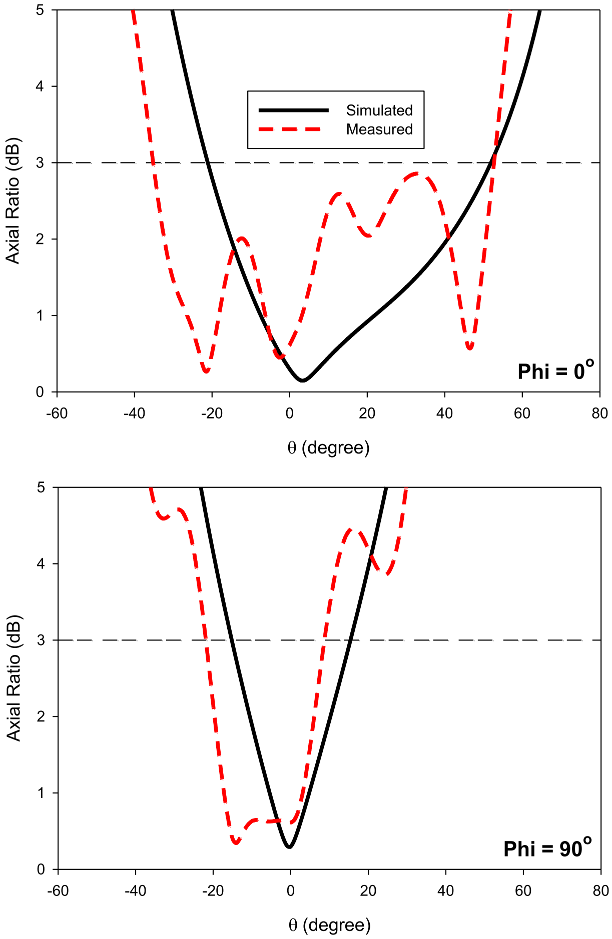


FIGURE 18. Beamwidth of the rectangular DRA fed by the H-shaped conformal metal strip at 3.8 GHz.

TABLE 1. Comparison between proposed antenna and other rectangular DRAs in literature.

Literature	ϵ_r	Excitation Technique	Mode	Usable CP Bandwidth (GHz)	Usable CP Bandwidth (%)	CP Beamwidth $\Phi = 0°\&90°$	Gain (dBic)	Applications
Ref. [16]	9.8	Conformal metal strip and parasitic patch	TE$_{111}$	3.29–3.45	2.7	Not available	4	WiMAX
Ref. [17]	9.2	Concentric Open Half-Loops metal strips	TE$_{111}$	3.1–3.55	14	115°&90°	5	WiMAX
Ref. [18]	9.8	Stair shaped microstrip line with a pair of L-shaped slots	TE$_{111}$	2.96–3.53	17.59	Not available	3.86	WiMAX
Ref. [19]	9.8	Question mark-shaped microstrip feed	TE$_{111}$	2.95–3.74	20.62	Not available	1.1	WiMAX
Ref. [20]	9.8	Triangular ring-shaped aperture and parasitic strip	TE$_{111}$	3.46–3.54	2.29	Not available	5	WiMAX
Proposed Antenna	10	H-shaped conformal metal strip	TE$_{113}$	3.67–4.4	20	89°&32°	6.8	WiMAX/Satellite communication

3.83 GHz, whereas the minimum measured value is 0.61 dB at 3.8 GHz. The small variations has been occurred in measured results due to the cable and connector losses occur in the measurement. These variations are more obvious at higher frequencies. An overlap of ∼100% has been observed between 3-dB AR and $|S_{11}| \leq 10$ dB bandwidths as presented in Figure 16.

A comparison between simulated and measured radiation patterns have been demonstrated in Figure 17. The antenna patterns have been measured and computed at three different frequencies. The antenna provides stable patters along the whole CP bandwidth. The antenna is left-hand polarized because the left-hand field component is dominant than its right-hand field component by a difference of more than 30 dB at minimum AR frequency in the broadside direction as depicted in Figure 17(b). Furthermore, right-hand polarization can be achieved by reversing the feeding strip.

The variation of AR as a function of elevation angle has been shown in Figure 18 at optimum AR frequency i.e. 3.8 GHz. A measured circular polarization with a useful beamwidth of $\sim 89°(-36°$ to $53°)$ has been offered by the antenna in $\Phi = 0°$ plane and $\sim 32°(-22°$ to $10°)$ in $\Phi = 90°$ plane. The beamwidths provided by the antenna are comparable to those reported in [11]. An expected AR asymmetry has been observed in principle plane because of asymmetrical location of the feeding strip in that plane. Moreover, the CP beamwidth of the proposed antenna make it useful for satellite communication [21].

The field distribution within the DRA can be approximated by a set of short magnetic dipoles. The gain of the DRA depends on the spacing between these adjacent dipoles and can be improved by increasing the spacing. The spacing between these adjacent dipoles can be increased by exciting the DRA in higher-order mode [28].

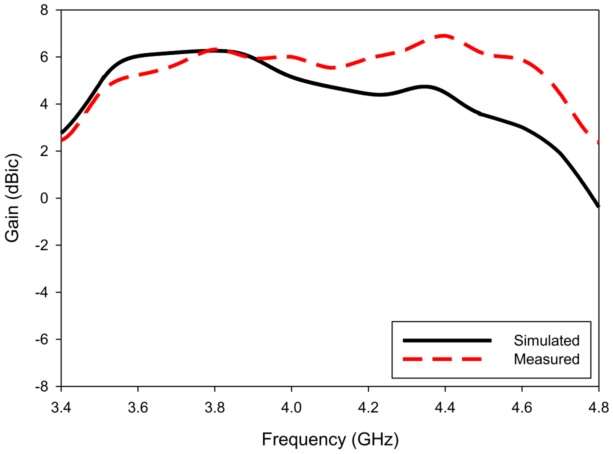


FIGURE 19. Gain of the rectangular DRA fed by the H-shaped conformal metal strip.

The simulated and measured gain comparison of the rectangular DRA has been demonstrated in Figure 19. The antenna provides a stable broadside gain. A useful gain of ∼6.8 dBic has been provided by the antenna along the whole CP bandwidth. The gain improvement has been made by exciting the rectangular dielectric resonator in first higher-order mode TE$_{113}$ and is a significant improvement to those reported in literature at similar frequency range at shown in Table 1.

From Table 1, it has been concluded that proposed CP antenna is better in terms of broadband axial ratio, beamwidth, and high consistent gain throughout the CP bandwidth compared to CP rectangular DRAs at similar frequency range.

V. CONCLUSION

A singly fed circularly polarized rectangular dielectric resonator antenna has been designed using a unique H-shaped conformal metal strip. A 3-dB axial ratio bandwidth of ∼20% has been measured, which is a good contribution to those achieved in previous studies. An impedance-matching bandwidth ($|S_{11}| \leq 10$ dB) of ∼27.7% has been measured over same frequency range. As evident from the far-field patterns the circular polarization has been achieved over a beamwidth of ∼89° in $\Phi = 0°$ plane and ∼32° in $\Phi = 90°$. A useful gain of ∼6.8 dBic has been offered by the antenna. Furthermore, broad CP bandwidth and beamwidth have been attained using a simple design configuration, and feeding strip has been constructed using an adhesive copper tape. A similar trend in simulated and measured results have been observed.

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