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Design and Analysis of Wideband Circularly Polarized Antenna Loaded with Ring Structure

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ABSTRACT: In this design, a wideband circularly polarized slot antenna loaded with rectangular ring is designed and validated. The square slot antenna is etched on an FR4 substrate with the calculated dimensions at the resonant frequency of 5 GHz. The square slot antenna is truncated in its corners to obtain two degenerative modes which are orthogonal to each other, and they are required to produce circular polarization. The truncation is optimized to obtain circular polarization. Wide CP bandwidth is achieved by selectively spacing the degenerative modes far in frequencies and loading the ring on the slot antenna. The ring and truncated slot antenna dimensions are optimized to achieve broad axial ratio bandwidth. The design is fabricated and experimentally verified. The measured impedance bandwidth of 47.53% is achieved at the center frequency of 5.68 GHz. The measured axial ratio bandwidth of 39.27% is obtained at the center frequency of 5.55 GHz. The peak gain of the antenna is 3.8 dBi with variation of 1–2 dBi over the entire bandwidth. The simulated radiation efficiency of more than 80% is obtained in the entire bandwidth with a cross polarization level of -20 dB with respect to co-polarization. The proposed design is compact and best suitable for NR46, NR47, NR79, N102, and N104 bands of 5G and C band wireless applications.

1. INTRODUCTION

The emerging wireless technology requires antennas that operate in wider bandwidth, which enables researchers to carry out the work with respect to wideband antennas with compactness using different techniques. Also, these antennas require circular polarization in order to avoid interference, Faraday's rotation effect, and orientation issues to receive the signal effectively. Some literature renegading wideband circular polarization (CP) antennas is presented here. A wideband CP antenna is designed to operate over a wide axial ratio bandwidth using 3D printing to connect the stacked patches with vias [1]. Wide bandwidth is achieved in [2] using crossed dipoles with a wideband feeding network and parasitic patches in [3]. Circular polarization is an essential component in 5G and mobile communication to accommodate more users which is achieved in [4]. A novel asymmetric Y-shaped arms based antenna is designed to obtain wideband CP in [5] and tightly coupled monopole in [6]. Nowadays, metasurface based antennas are popular to obtain wideband circular polarization due to its potentiality in altering the resonances and orthogonal modes. A few metasurface based designs are proposed in the literature to obtain wideband CP [7] using polarization conversion metasurface, single layer metasurface [8], nonuniform metasurface [9], metasurface plane for bio-telemetry application [10], and conformal metasurface [11]. Characteristic mode based metasurface antennas are analyzed in [12] and [13] to achieve wideband CP. Also, a hybrid metasurface with coplanar waveguide (CPW) feed achieves wideband CP in [14] and application like Global Navigation Satellite System (GNSS) signal detection utilizes wideband CP in [15]. Above designs have disadvantages in terms of complexity in design, high profile, narrow axial ratio bandwidth, and complex feeding network. To overcome all the above problems, an antenna with compactness, low profile, and wide axial ratio bandwidth is proposed in this article.

A compact slot antenna loaded with a ring is designed for a wide band circular polarization application. A square slot antenna is first designed to get a fundamental resonance frequency. The corners of the slot antenna are truncated to obtain two degenerative modes required to obtain circular polarization near 5 GHz. Then, ring is loaded to obtain circular polarization at the higher resonance of 6 GHz. The orthogonality of slot and ring produce CP in the higher frequency band. The combined orthogonality of slot and ring gives wide axial ratio bandwidth. With this compactness, authors achieve a better impedance and axial ratio bandwidth than some of the recent literature which is provided in the state of the art table.

2. DESIGN AND ANALYSIS OF THE ANTENNA

The geometrical structure of the antenna is designed using a low cost FR4 substrate ($\epsilon_r = 4.3$ and $\tan\delta = 0.025$), which is shown in Fig. 1. A slot is etched in the front side of the substrate. A microstrip feed line is printed on the backside of the substrate. The resonant frequency of the slot is designed using Equation (1). The square slot resonates in its fundamental

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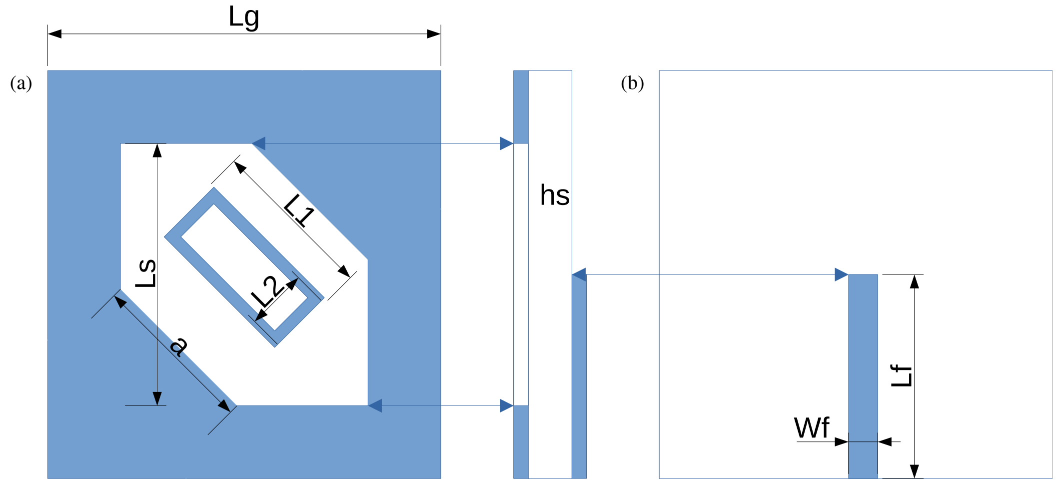

FIGURE 1. Antenna structure: $Lg = 50$ mm, $Ls = 32$ mm, $a = 12.7$ mm, $L1 = 16$ mm, $L2 = 10$ mm, $W = 1$ mm (width of the ring strip), $Wf = 3.1$ mm, $Lf = 23$ mm.

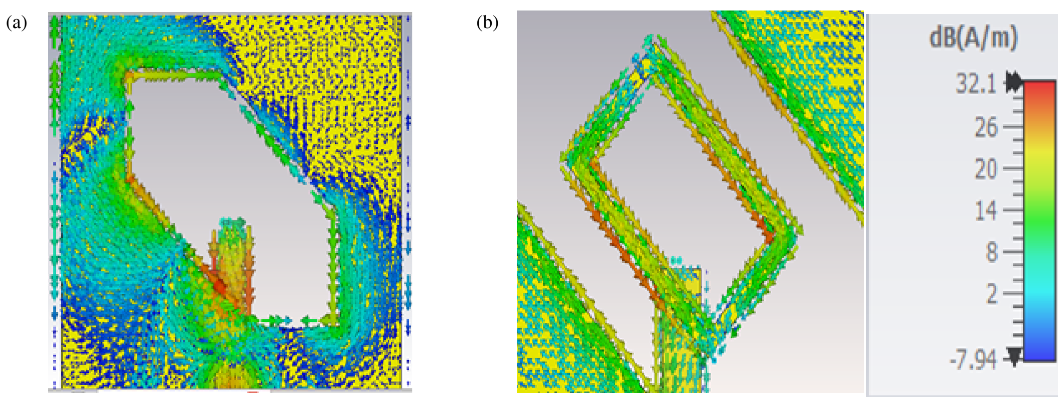

FIGURE 2. Surface current distribution of the (a) slot at 5 GHz and (b) rectangular ring at 6 GHz.

mode. The corners are truncated to generate two degenerative modes which are far in frequency to produce circular polarization.

$$fr = \frac{C}{2L_s}\sqrt{\frac{2}{1+\epsilon_r}} \tag{1}$$

The surface current distribution at 5 GHz is shown in Fig. 2(a), and it is evident that the slot produces its resonance. The surface current on the rectangular ring is shown in Fig. 2(b), and it resonates at 6 GHz. The electric field distribution of the corner modified slot antenna is shown in Fig. 3. It shows that the electric field is rotating clockwise direction with respect to $+z$-direction, and it can be predicted as left hand circular polarization (LHCP). The axial ratio bandwidth is enhanced by loading the rectangular ring on the slot. The orthogonal modes of ring and slot produce circular polarization in the higher band. The surface current shows that the vectors are orthogonal in diagonal direction as seen in Fig. 2(b).

It is shown that the vectors are in orthogonal direction and produce LHCP. The equivalent circuit of the proposed design is shown in Fig. 4. The slot is excited with microstrip line feed which is basically an RLC circuit. When the ring is magnetically coupled from the slot, it introduces an LC resonant circuit. The values of LC circuits are realized, and it is simulated in Advanced Design System (ADS) to check the circuit validation. The results of electromagnetic (EM) simulation and circuit simulation are in good agreement with little variation due to losses. The S_{11} is shown in Fig. 4(c). The equivalent circuit schematic values are $Ls = 1$ nH, $Cc = 0.44$ pF, $L1 = 0.25$ nH, $C1 = 2.26$ pF, $R1 = 0.78\,\text{k}\Omega$, $L2 = 0.25$ nH, $C2 = 2.26$ pF, $Cp = 1.89$ pF.

3. RESULTS AND DISCUSSION

The proposed antenna is fabricated as shown in Fig. 5. To validate the design, the fabricated design is experimentally measured using vector network analyzer and anechoic chamber facility. The simulated impedance bandwidth ranges from 4.42 GHz to 7.12 GHz (46.78%) at the center frequency of 5.77 GHz. The measured impedance bandwidth has little variation ranging from 4.33 GHz to 7.03 GHz (47.53%) at the center frequency 5.68 GHz, shown in Fig. 6(a). The comparison between simulated and measured axial ratios is provided

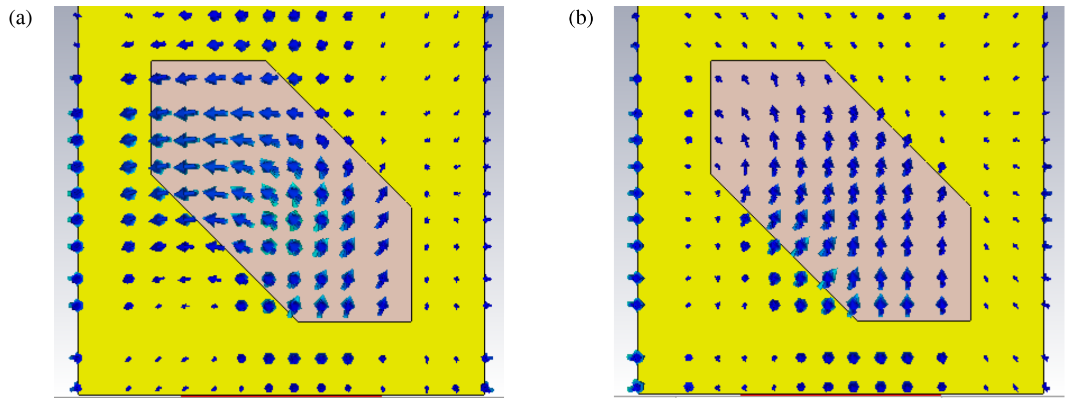

FIGURE 3. Electric field distribution of the slot at 5 GHz. (a) $\omega t = 0°$, (b) $\omega t = 90°$.

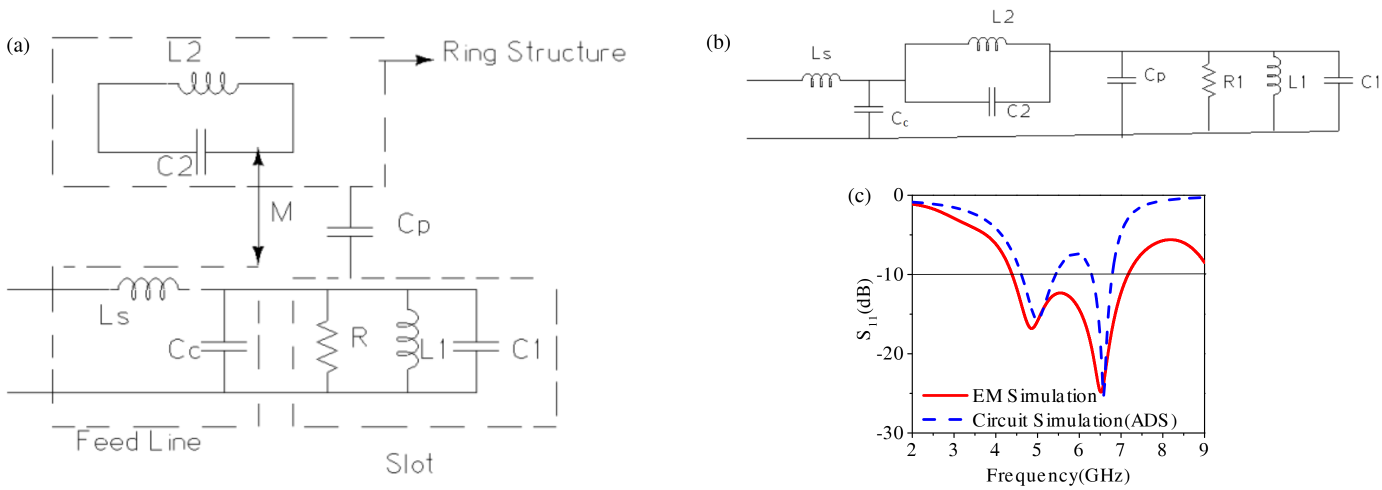

FIGURE 4. (a) Equivalent circuit of energy coupling form slot to ring, (b) equivalent circuit of proposed design, and (c) S_{11} comparison between EM and circuit simulation.

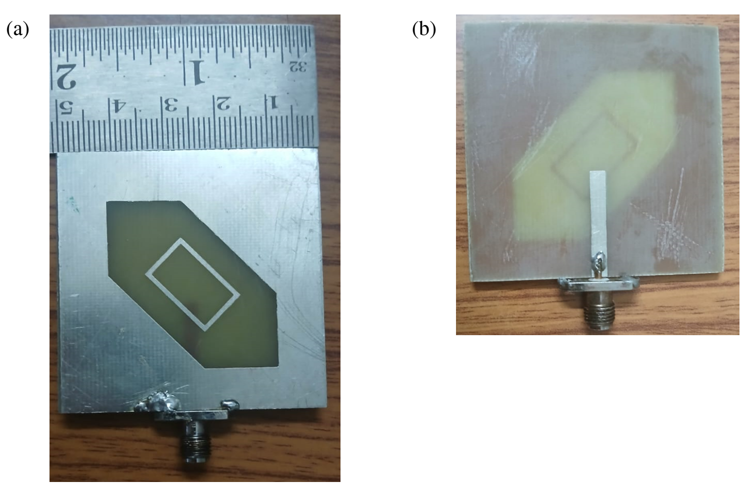

FIGURE 5. Fabricated antenna. (a) Front view. (b) Back view.

in Fig. 6(b). The simulated axial ratio bandwidth is in the range of 4.47 GHz–6.89 GHz (42.60%) at 5.68 GHz center frequency. The measured axial ratio bandwidth is from 4.46 GHz to 6.64 GHz (39.27%) at 5.55 GHz center frequency. The peak gain of 3.8 dBi is obtained at 5.8 GHz with 1–2 dBi variation over the entire bandwidth, given in Fig. 6(c).

The simulated radiation efficiency of more than 80% is maintained over the entire bandwidth, shown in Fig. 6(d). The sim-

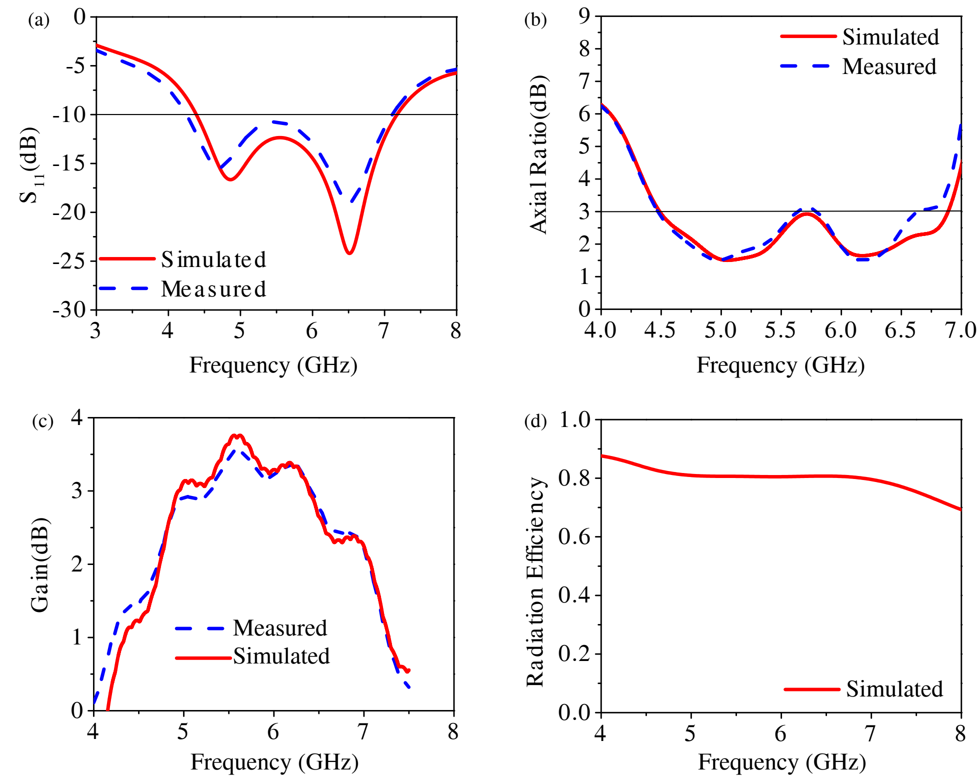

FIGURE 6. (a) Simulated and measured S_{11} (dB). (b) Simulated and measured axial ratios (dB). (c) Simulated and measured gains (dB). (d) Simulated radiation efficiency.

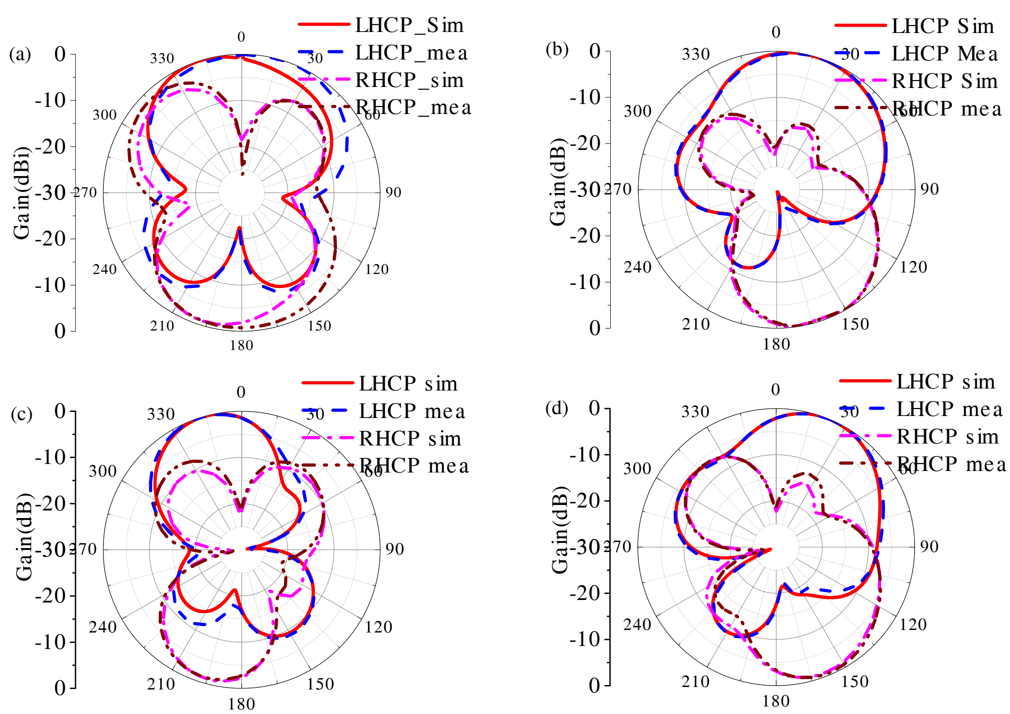

FIGURE 7. Radiation pattern of the proposed antenna at 5 GHz. (a) XZ plane, (b) YZ plane and at 6 GHz, (c) XZ plane, (d) YZ plane.

ulated and measured radiation patterns of the proposed design at 5 GHz and 6 GHz are shown in Fig. 7. The radiation pattern is tilted a little bit with respect to broadside direction due to truncation and diagonal orientation of the ring. LHCP is co-polarization, and right hand circular polarization (RHCP) is cross polarization. The cross polarization level of minimum -20 dB is obtained with respect to co-polarization. Table 1 provides the comparison of previous designs with the proposed one. The size of the antenna is comparable with a few of the designs. The axial ratio bandwidth is more than the other works.

TABLE 1. Comparison of proposed design with current state of the art.

[Ref]	Size ($\lambda_0 \times \lambda_0$)	*IBW (%)	*ARBW (%)	Gain (dBi)	*PS and ITFB
[8]	1.28×1.28	55.96	2.7	9.58	NA
[9]	0.8×0.8	48.74	19.92	9.35	NA
[11]	1.16×1.16	18.6	18.6	5.5	NA
[12]	0.71×0.71	25.4	20.2	7.1	NA
[14]	0.39×0.39	24.28	17.1	7.7	NA
[15]	0.45×0.45	56.97	11.38	6	NA
[Proposed]	0.94×0.94	47.53	39.27	3.8	Yes

*IBW = Impedance Bandwidth, *ARBW = Axial Ratio Bandwidth, *PS&ITFB = Polarization Sense and Independent Tuning of Frequency Bands

The gain and impedance bandwidth are comparable to other designs with an option of polarization sense and independent frequency tuning. By changing the corner truncation and ring orientation with respect to the other diagonal directions, tuning can be achieved.

4. CONCLUSION

In this work, a slot antenna with corner modification loaded with a ring like structure is proposed, and wideband circular polarization is obtained. The two orthogonal degenerative modes of modified corner slot produce good axial ratio bandwidth by placing modes fairly far apart. Further, the axial ratio bandwidth is enhanced using a ring like structure loaded on the slot. The ring and slots are orthogonal to each other and produce minimum axial ratio value in the higher frequency point in the bandwidth. Combining slot and ring structure enhances the axial ratio bandwidth to 39.27%. The antenna is experimentally verified with gain, axial ratio bandwidth, impedance bandwidth, and radiation pattern parameters. This design is well suitable in C band radar, satellite, and NR bands of sub-6 GHz 5G communication.

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