Novel Design and Characterization of Wide Band Hook Shaped Aperture Coupled Circularly Polarized Antenna for 5G Application

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Abstract—This research paper presents a wideband hook shaped aperture coupled circularly polarized antenna for 5G application. It consists of three layers; a radiating copper plate (0.5 mm) as a top layer, a foam material of 2 mm thickness as a middle layer, an FR4 substrate with hook-shaped apertures in the ground plane, and a bent feed line as the bottom layer. The performance characteristics of the proposed design are improved by feeding mechanism, which entails the use of a bent shape microstrip line coupling through four hook shaped slots to generate four sequentially phased sources to excite the single layer patch antenna. The proposed antenna exhibits the return loss bandwidth of 29.10% (2.8–3.81 GHz), axial ratio bandwidth of 13.47% (3.61–4.11 GHz), and cross polarization level is 20 dB which is attained at bore sight and gain of 4.08 dBic at the resonant frequency of 3.47 GHz. The proposed antenna design is fairly applicable to 5G radio band and discussed about the azimuth, elevation patterns, and surface current distribution in frequency band of interest. The proposed design is simulated using High frequency structure simulator (v.13), and measured results are in good agreement with simulated ones.

1. INTRODUCTION

The evolution of 4 generations of technology brought massive changes and growth in mobile wireless communication. To overcome the shortcomings of 4G, a new generation is evolved as 5G and is expected to fulfil better reliability, better connectivity, lower latency, higher data rate, and better quality of service. To ensure high speed reliable data and video transmission, wideband antenna elements with excellent frequency and time domain characteristics are essential. Therefore, developing low profile antennas satisfying all the above characteristics simultaneously is a hot topic of recent research. To achieve the above characteristics, an essential component is microstrip antenna.

Microstrip antennas are preferred due to low profile, compactness, suitability for supporting structure, flexibility, and ease of fabrication. However, microstrip antennas suffer from low bandwidth. Meanwhile, circularly polarized antennas are in demand because of insensitivity to antenna orientations, elimination of the signal Faraday rotation effect caused by the ionosphere, and resistance to bad weather condition [1]. Some of the circularly polarized (CP) designs, such as helix antenna, conical log spiral antenna, and skew-planar wheel antenna have good performance. However, one of their major limitations is their bulky size, especially for portable wireless devices. To enhance the bandwidth with compact circular polarisation, various techniques have been reported in literature such as slits [2, 3], slots [4], capacitive loading, and inductive loading [5]. With these techniques, impedance bandwidth can be improved, but axial ratio is narrowed. Magnetoelectric dipoles with reconfigurability [6], L-probe [7], and stacking of patches are used [8, 9], but the size of the antenna is generally large. Besides, the antenna characteristics can be met by optimizing the substrate parameters of the radiating patch without having to increase the antenna size significantly in aperture coupled feeding mechanism. This feeding mechanism is useful since the optimization of the feed position and radiating patch design are

carried out independently. Various apertures have been proposed in the literature, such as cross slot, C-shaped slot, square slot ring, and square slot to couple the power to various shapes of patches [10–17]. In this paper, a novel three-layer hook-shaped aperture coupled antenna structure is discussed for 5G applications, with improved bandwidth, gain, and axial ratio. Section 2 discusses the details of the composite geometry. A parametric study for investigating the effect of the thickness of the substrate and shorting strip is first carried out on performance of the proposed design in Section 3. Section 4 discusses results and discussion.

2. ANTENNA STRUCTURE

The designed structure uses a minimized ground, apertures on one side of the substrate, foam in between the substrate and a copper patch, and a shorting pin at the edge of the feed line. The antenna is designed on an FR4 substrate ($\varepsilon_r = 4.4$) with thickness $h = 2\,\mathrm{mm}$, as shown in Fig. 1. Four hook-shaped apertures are placed at $90°$ to each other in the ground plane out of which one is smaller in size to generate asymmetry, which results in circular polarization. A feed line is designed on the other side of the substrate and is bent to increase the electrical length. A foam of thickness $2\,\mathrm{mm}$ is placed on top of the substrate with hook-shaped apertures. A rectangular copper radiating patch of thickness $0.5\,\mathrm{mm}$ is placed on top of the foam. The foam layer helps in the enhancement of bandwidth.
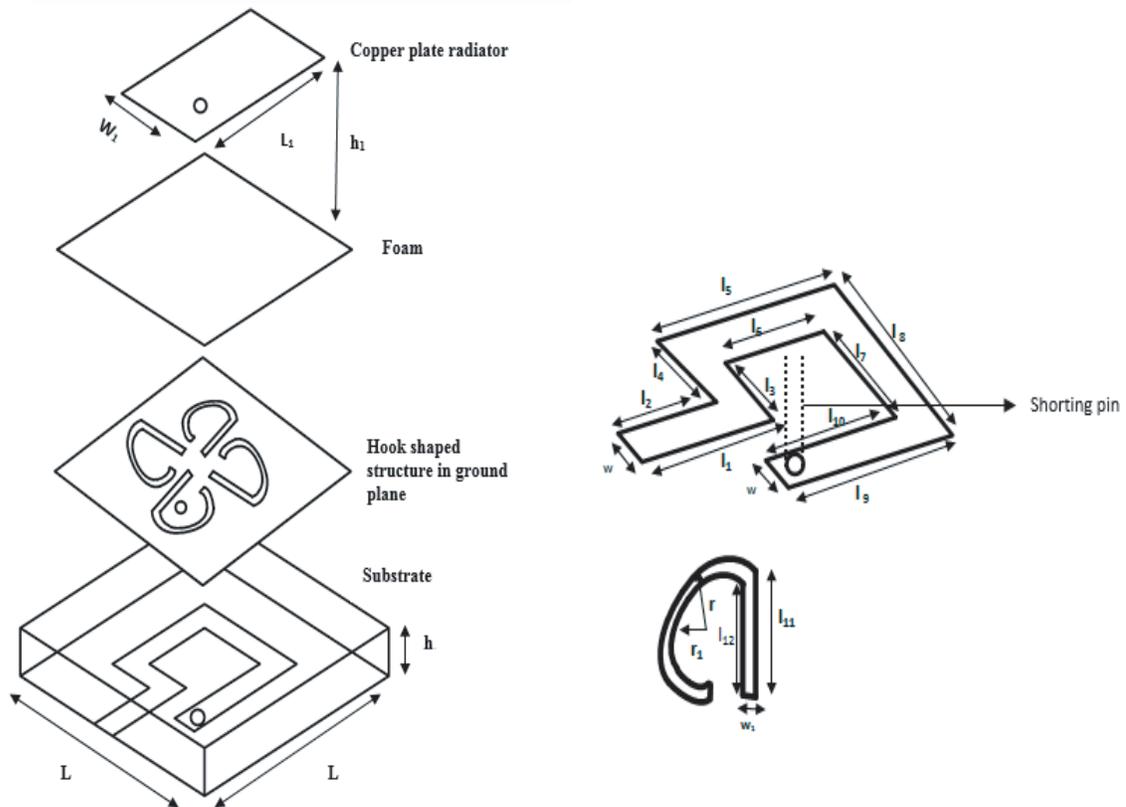

Figure 1. Top view, feed line, and aperture of the novel hook shaped aperture coupled circularly polarized antenna.

Further, a shorting pin of radius $1.2\,\mathrm{mm}$ is used to connect the feed line and the radiating patch through a hole in the ground plane. This arrangement couples more power to the radiating patch in addition to the power coupled through hook-shaped apertures. The shorting pin also reduces spurious radiation. Table 1 shows various dimensions, and Fig. 2 shows the structure of the antenna. When a shorting pin is connected to the patch, an inductance is introduced in parallel, which results in frequency
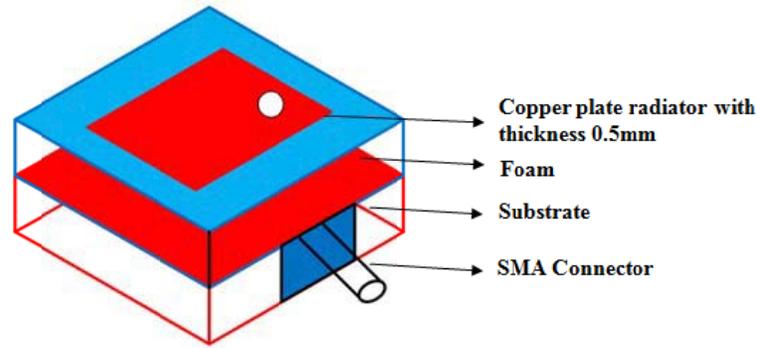
Figure 2. Overview of the proposed novel hook shaped aperture coupled circularly polarized antenna.

Table 1. Description of parameters.

S. No.	Parameter	value (mm)
1	l_1	11.5
2	l_2	8.5
3	l_3	8.5
4	l_4	11.5
5	l_5	15
6	l_6	9
7	l_7	11
8	l_8	14
9	l_9	15
10	l_{10}	12
11	l_{11}	6
12	l_{12}	5.5
13	L	36
14	h	2
15	w_1	0.5
16	L_1	28
17	W_1	24
18	w	2
19	h_1	2
20	r	5.42
21	r_1	5.92
22	r (smaller hook)	5.23
23	r_1 (smaller hook)	5.73
24	ε_r	4.4

tuning and can be used to control the dual-frequency separation. A shorting pin is introduced near the edge of the feed line to strengthen the surface current density and reduce the higher-order modes near the vicinity of the pin. It helps in the reduction of the size of the patch, proper impedance matching, and low cross-polarization [18–22].

Generally, the patch resonates at half-wavelength, and its length is large. Reducing the resonant

length to half, by placing a short at fundamental mode where the electric field is zero, results in the quarter-wave patch, which has an area about one-fourth of the regular patch.

The use of one or more shorting pins can reduce the size of the patch to about one-ninth of the area of the original regular patch. From the entire design, the line feed acts as a probe feed with the help of aperture structure and shorting pin. When the power is fed through feeding mechanism, four hook shaped slots are coupled to each other and result in sequential phased sources to excite the patch antenna.

2.1. Aperture Geometry details

Figure 3 shows the aperture design. Consider that $(x_1, y_1), (x_2, y_2), (x_3, y_3)$ are the three points on the arc; (h, k) is the center of the arc; and r is the radius of the arc.

$$\text{Equation of a circle } (x - h)^2 + (y - k)^2 = r^2 \tag{1}$$
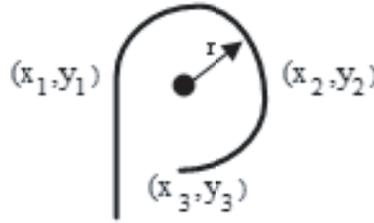

Figure 3. Circular arc-shaped aperture for the proposed design.

Substituting $(x_1, y_1), (x_2, y_2), (x_3, y_3)$ in Equation (1), we get 3 equations, and the unknowns (h, k) and radius r are calculated.

3. PARAMETRIC ANALYSIS

3.1. Variation of Return Loss with Respect to Thickness

The proposed antenna is designed on an FR4 substrate with $(\varepsilon_r = 4.4)$, and parametric analysis is done for thicknesses 1.6 mm, 2 mm, and also by varying the radiating patch size as 28×24 mm and 26×24 mm as listed in Table 2. According to Table 2, return loss bandwidth is higher for thickness 2 mm with patch size 28×24 mm. For the 2 mm thickness of the substrate with radiating patch size 26×24 mm,

Table 2. Comparison of Return loss for various thicknesses of substrate.

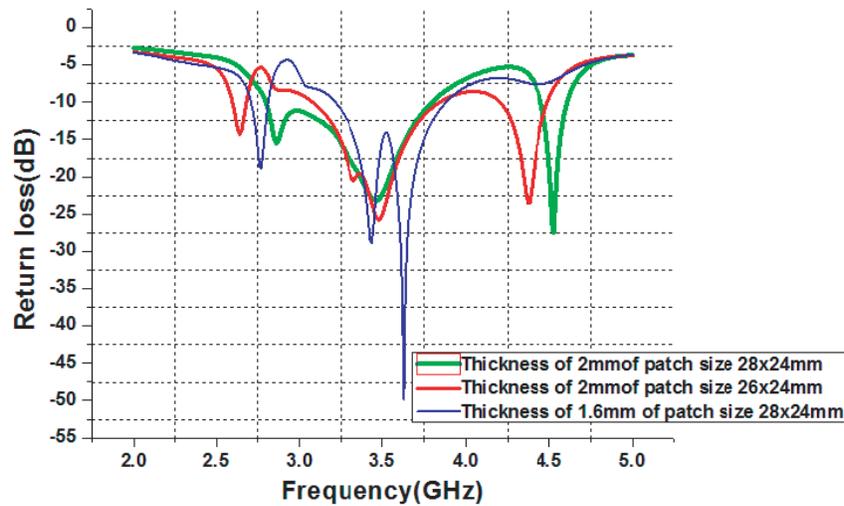| S. N.	Thickness of the substrate (mm)	Radiating patch size (mm)	Resonant Frequencies (GHz)	Return loss bandwidth (%)	Range (GHz)
1	2	28 × 24	3.47	29.10	2.8–3.81
			4.53	3.53	4.45–4.61
2	2	26 × 24	2.64	3	2.6–2.68
			3.49	21.7	3.08–3.84
			4.37	6.4	4.21–4.49
3	1.6	28 × 24	2.77	3.6	2.71–2.81
			3.63	18	3.22–3.88

Figure 4. Return loss for various thicknesses of novel hook shaped aperture coupled circularly polarized antenna.
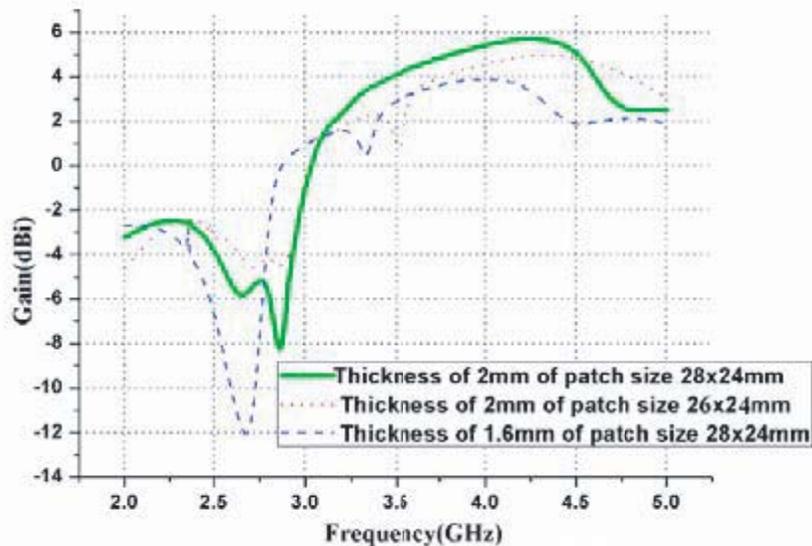

Figure 5. Gain for various thicknesses of novel hook shaped aperture coupled circularly polarized antenna.

the antenna resonates at three bands, but the bandwidth and gain are low compared to others. So the 2 mm thickness of substrate with patch size 28 × 24 mm is opted as illustrated in Figs. 4–5.

3.2. Variation of Return Loss and Gain with and without Shorting Pin

For the proposed design, a shorting pin at the edge of the feed line to the top of the radiating patch results in wide impedance bandwidth. At the resonant frequency of 3.47 GHz, the bandwidth and gain are 1.01 GHz and 4.08 dBi. Without shorting pin impedance bandwidth is more, but gain is reduced at the resonant frequency. The return losses and gains, without and with shorting pin are shown in Figs. 6–7 and Table 3.
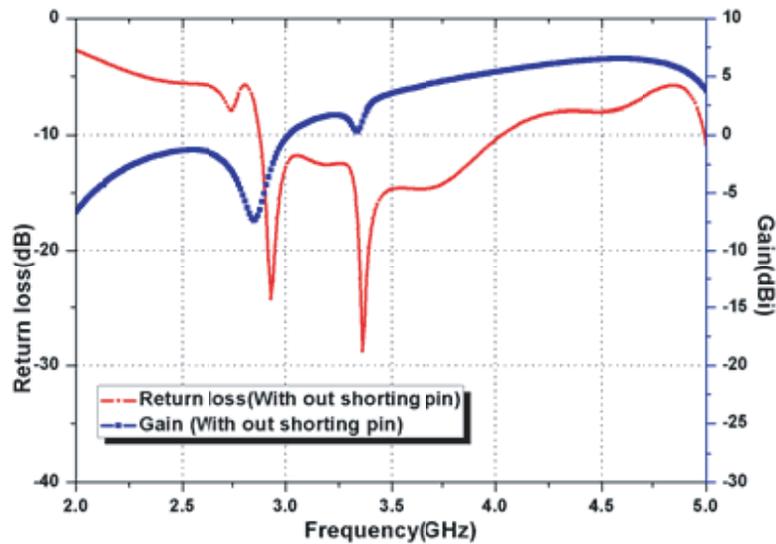
Figure 6. Return loss and gain performance without a shorting pin of novel hook shaped aperture coupled circularly polarized antenna.
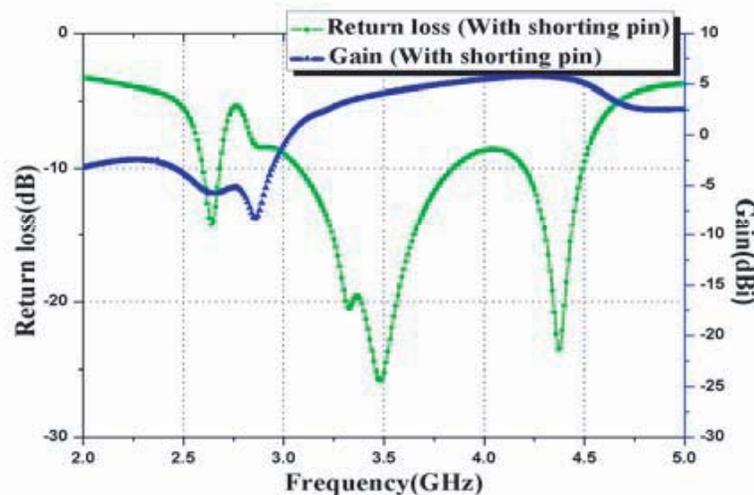

Figure 7. Return loss and gain performance with a shorting pin of novel hook shaped aperture coupled circularly polarized antenna.

3.3. Variation of Return Loss and Gain with the Height of the Shorting Pin and Width of the Feed Line

Two parameters are varied with respect to design, i.e., the height of the shorting pin and feed line strip width. By varying the height of the shorting pin and strip width (w), the impedance bandwidth and gain are studied at the resonant frequencies and shown in the Table 4 and Fig. 8.

To achieve a wide band performance, firstly a study on various thicknesses of the substrate is carried out to enhance the bandwidth of the proposed design as shown in Fig. 4. A shorting pin is used in the ground plane to strengthen the surface current density and compactness of the design. The performance of the proposed design is improved as seen in Figs. 5–8.

Table 3. Effect of shorting pin on the performance characteristics of the hook shaped aperture coupled circularly polarized antenna.

S. No.		Return loss bandwidth (GHz) at the resonant frequency	Gain (dBi) at resonant frequency
1	Without Shorting pin	1.15 GHz at 3.36 GHz	1.146
2	With Shorting pin (height = 4 mm)	1.01 GHz at 3.47 GHz	4.08

Table 4. Effect of the height of a shorting pin and width of strip line on hook shaped aperture coupled circularly polarized antenna.

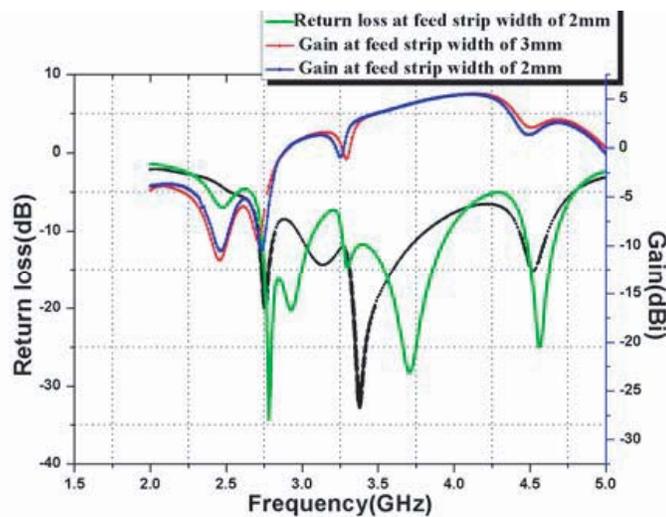| S. No.	Height of the shorting pin	Return loss bandwidth (MHz)	Gain (dBi)
1	2 mm height, width strip of 3 mm	830	2.62
2	2 mm height, width strip of 2 mm	650	4.52
3	4 mm height, width strip of 2 mm (optimum)	1100	4.08

Figure 8. Return loss and gain performance with respect to the height of the shorting pin for novel hook shaped aperture coupled circularly polarized antenna.

4. RESULTS AND DISCUSSION

A novel hook shaped aperture coupled circularly polarized antenna is fabricated using an FR4 substrate, foam and copper plate of thickness 0.5 mm is shown in Fig. 9.

4.1. Return Loss

The performance of the fabricated design is obtained by a major parameter called return loss. The return loss at the resonant frequency of 3.47 GHz is 23 dB, and the obtained impedance bandwidth ($<= -10$ dB) is 29.10% (2.8–3.81 GHz). The resonant frequency of the proposed design falls in the 5G band, which is shown in Fig. 10.
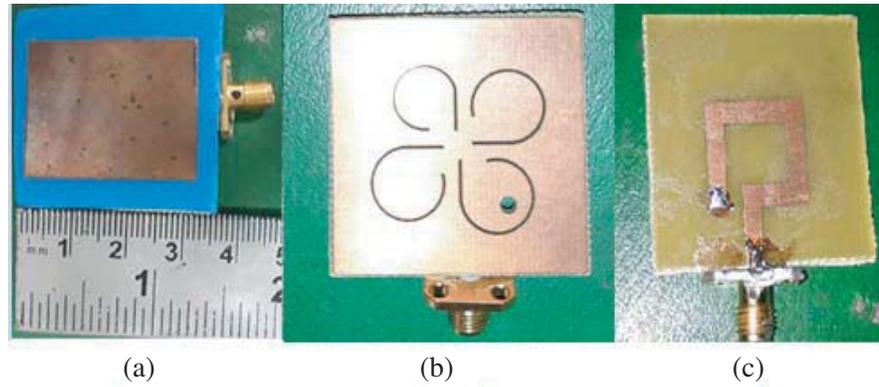
(a)   (b)   (c)

Figure 9. Fabricated hook shaped aperture coupled circularly polarized antenna. (a) Top view. (b) Aperture. (c) Feed line structure.
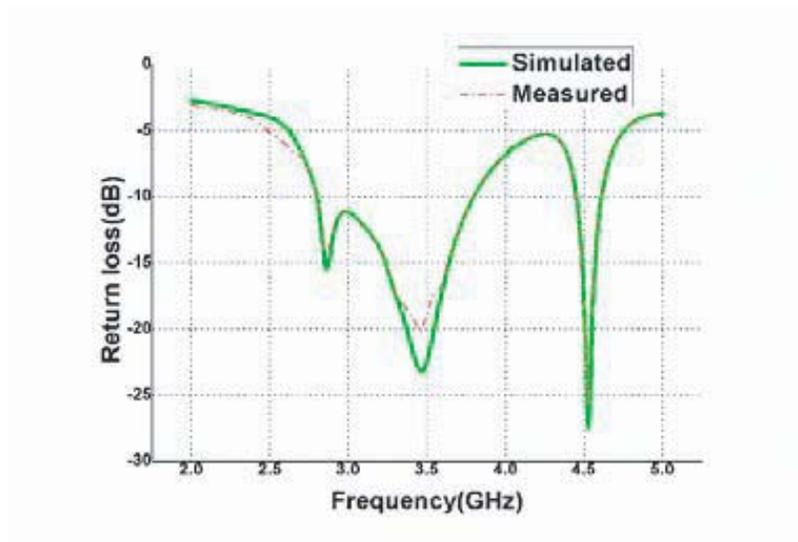

Figure 10. Return loss for the hook shaped aperture coupled circularly polarized antenna.

4.2. Axial Ratio

It is the ratio of orthogonal electric fields in circular polarization. The axial ratio for the fabricated antenna is 13.47% (3.61–4.11 GHz), as shown in Fig. 11. It helps the proposed design maintain the optimum circular polarization from the positioning of the transmitting or receiving antenna. Cross polarization discrimination (CPD) is calculated using axial ratio as shown below [28] and obtained of 48.54 dB.

$$\text{CPD} = 20 * \log \frac{(ar + 1)}{(ar - 1)} \tag{2}$$

4.3. Gain

The gain at the resonant frequency of the fabricated antenna is 4.08 dBic and is shown in Fig. 12. Azimuth and elevation radiation patterns are shown in Fig. 13. VSWR (Voltage standing wave ratio) reading is 1.148 for the fabricated antenna and shown in Fig. 14. Front to back ratio for the proposed aperture coupled circularly polarized antenna is 17.8 dB. Figs. 15(a) and (b) indicate the co-polarization and cross-polarization for E- and H-planes, and the isolation of greater than 20 dB is observed.
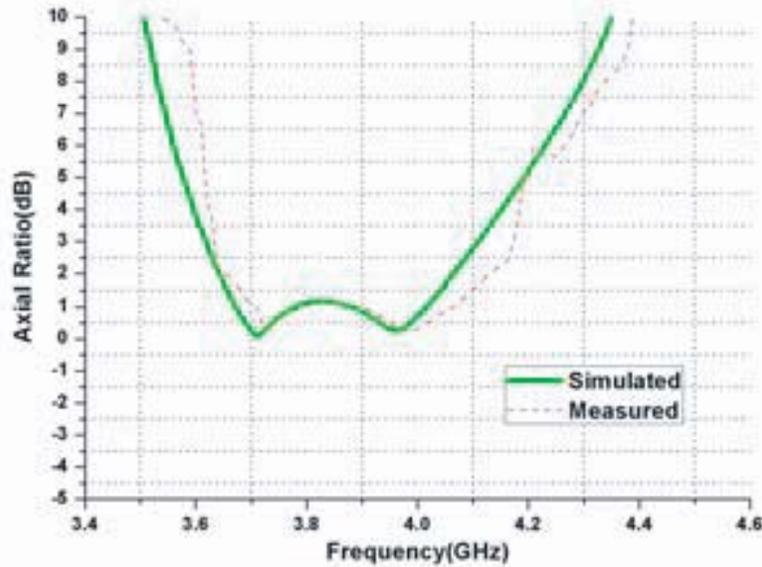
Figure 11. Axial Ratio for the hook shaped aperture coupled circularly polarized antenna.
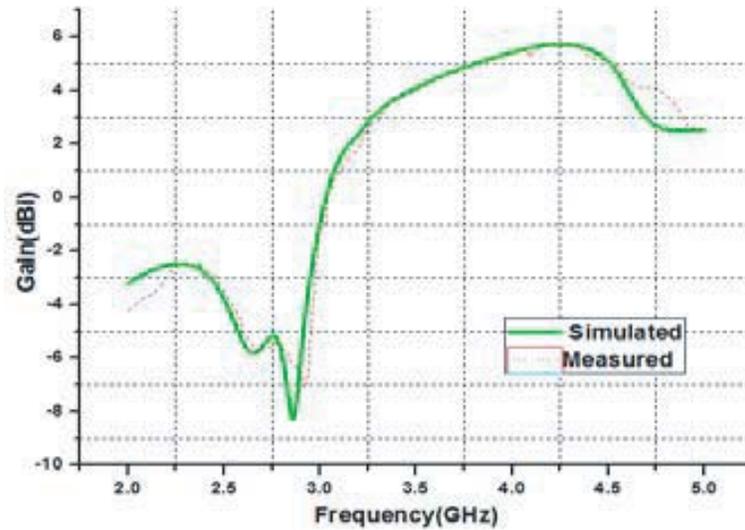

Figure 12. The gain of the hook shaped aperture coupled circularly polarized antenna.

4.4. Surface Current Distribution

Figure 16 shows the current distribution on the radiating patch of the proposed design at the resonant frequency 3.47 GHz. Here the number of frames is 16 which is divided into 4 divisions as $t = 0$, $T/4$, $T/2$, and $3T/4$. At $t = 0$, $T/2$ current density is heavy and uniform at all the corners. For $t = T/4$, $3T/4$ current floats at the center more than the edges. Fig. 17 shows the aperture current distribution at the resonant frequency. Here the field changes from one hook to the other at all four cycles. When the electromagnetic energy is radiated by a feed line, the power is sequentially coupled from one hook to the other which can be seen in the current distribution.
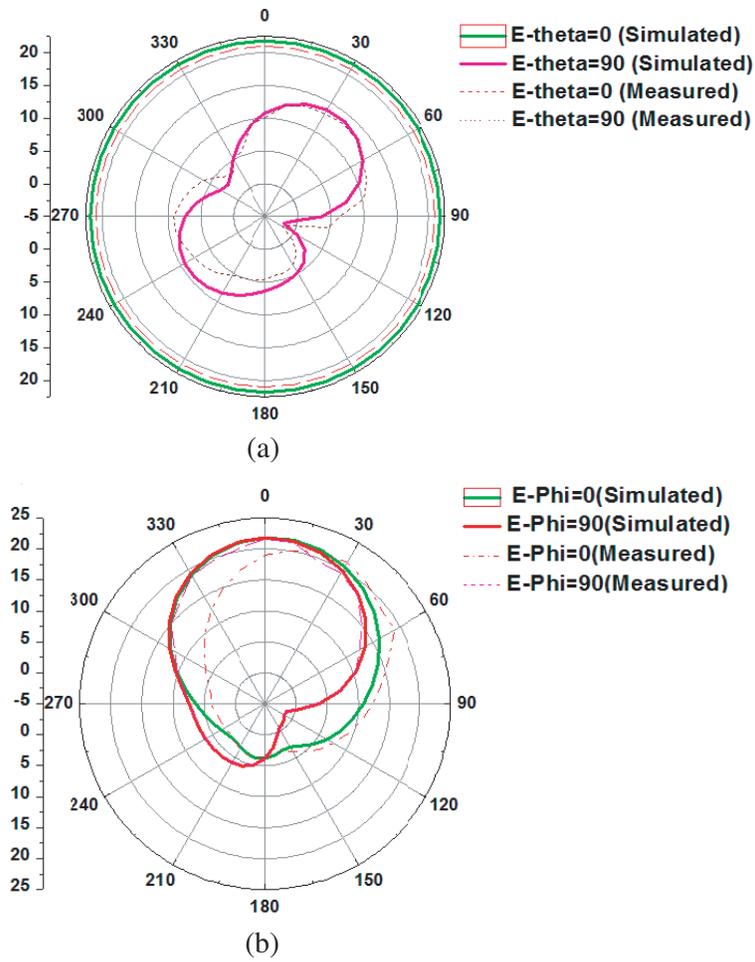
(a)

(b)

Figure 13. Azimuth Pattern and Elevation pattern of the hook shaped aperture coupled circularly polarized antenna at a resonant frequency of 3.47 GHz.
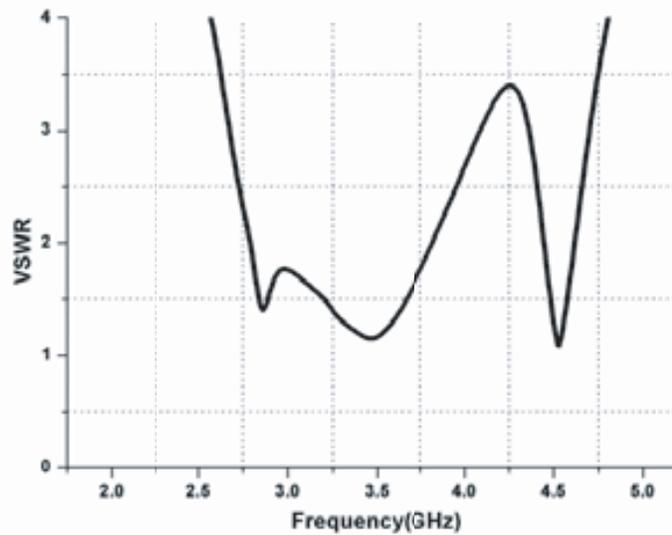

Figure 14. Simulated VSWR of the hook shaped aperture coupled circularly polarized antenna.
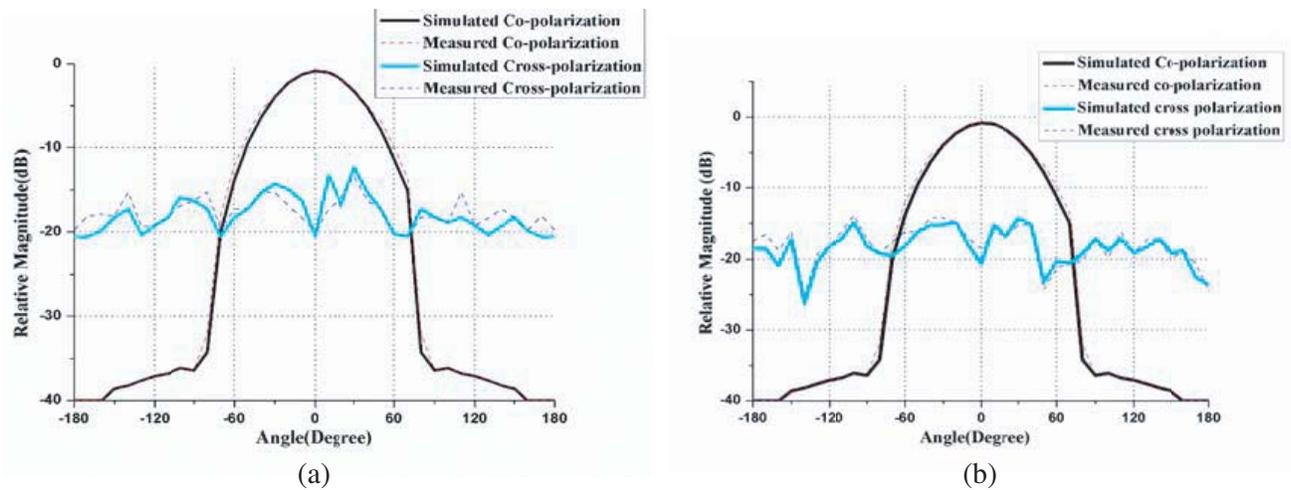
Figure 15. Co-polarization and cross-polarization at resonant frequency 3.47 GHz for E-plane and H-plane for hook shaped aperture coupled circularly polarized antenna.
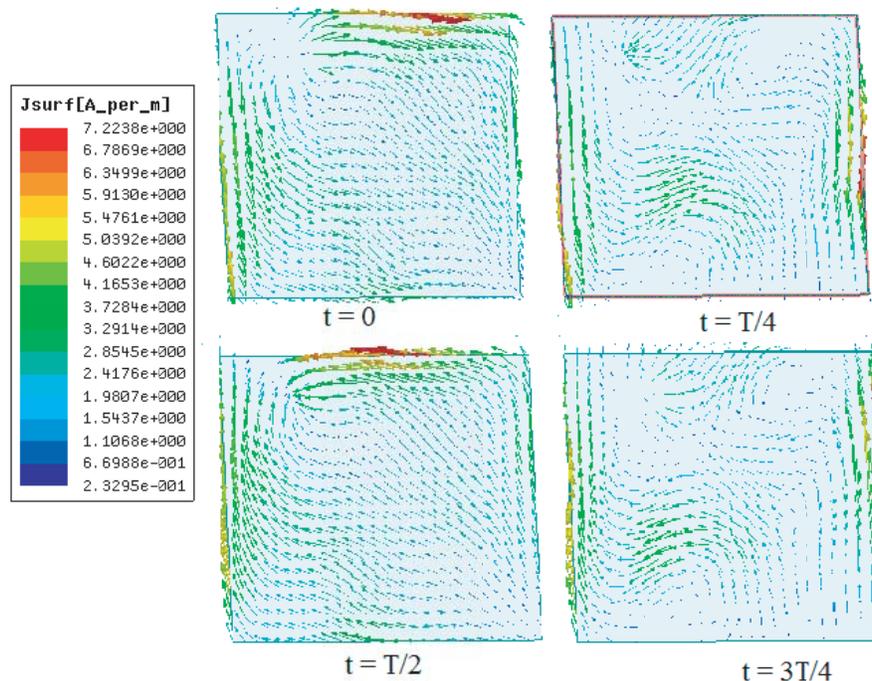

Figure 16. Surface current distribution at the resonant frequency 3.47 GHz for hook shaped aperture coupled circularly polarized antenna.

4.5. Measurement Set up

When an antenna is fabricated with a finalized design on the performance by measuring its performance parameters like return loss, axial ratio, gain, radiation efficiency, and radiation characteristics using the Network Analyser and antenna measurement setup. Here are mostly two types of network analyzers available: scalar and vector network analyzers. Scalar network analyzer measures the magnitudes of transmission and reflection coefficients; however, both the magnitude and phase of the S-parameters are measured by the vector network analyzer. In general, the network analyzer consists of a signal processor,
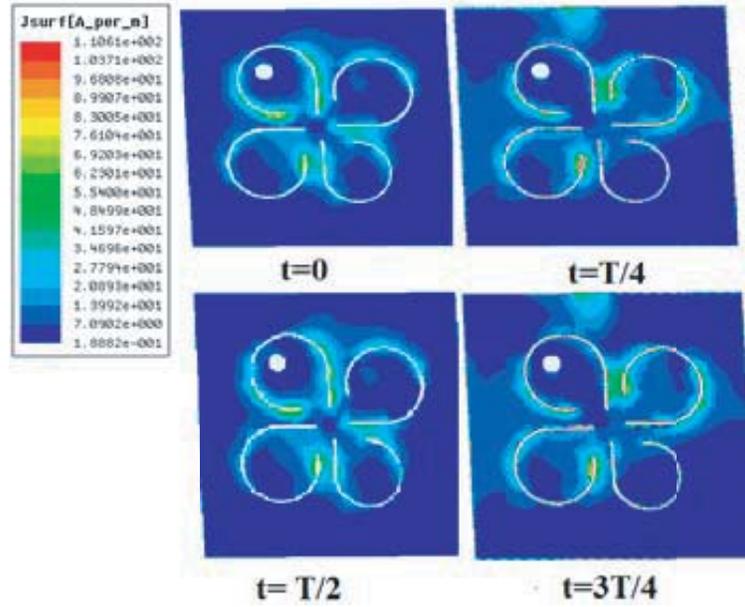
Figure 17. Aperture Surface current distribution at the resonant frequency 3.47 GHz for hook shaped aperture coupled circularly polarized antenna.

(a)   (b)

Figure 18. Measurement of return loss for the hook shaped aperture coupled circularly polarized antenna and proposed antenna prototype.

calibration kit, display unit, and microwave source. To evaluate the performance, parameters of the antenna using a vector network analyzer are calibrated once the ports are matched. After the matching is done, the antenna is connected to port 1 and matched load to port 2. Fig. 18 illustrates the measured return loss for the proposed antenna. Axial ratio of the fabricated antenna is measured using swept-frequency method [27]. A comparison between existing designs to the proposed is listed in Table 5.

Procedure for measurement is descried as follows.

1. Switch on the network analyser 8719A (130 MHz–13.5 GHz), and set up the start frequency and end frequency. In this case, start frequency 2 GHz and end frequency 5 GHz are set up using start and end frequency buttons in the network analyser.

2. To check matched condition, i.e., No reflections, Connect two port. In menu, click on CAL button, then select Calibration menu; go to response; select thru; and click done.

3. If there are reflections connect port1 to matched load and select CAL button in menu, go to

Table 5. Comparison of various techniques with the hook shaped aperture coupled circularly polarized antenna.

S. No.	References	Resonant Frequency (GHz)	Impedance Bandwidth (MHz)	Gain (dBi)	Axial ratio Bandwidth (MHz)	Front to back ratio (dB)	CPD (dB)	Size of the antenna (mm)
1	[23]	3.5, 5.8	105, 864	6.2, 6.5	69, 179.8	-	-	50×50
2	[24]	3.63, 5.1	228, 232	6.11, 0.14	-	-	-	$2 \times 76 \times 3.14$
3	[25]	3.5	500	8	200	-	-	$21 \times 21 \times 36.124$
4	[26]	3.5	200	8.1	-	-	-	$70 \times 70 \times 5.5$
5	Proposed	3.47	1100	4.01	500	17.8	48.54	$36 \times 36 \times 4$

calibrate kit and select N50Ω.

4. Connect antenna via two sided female pin to port 1 as shown in Fig. 2. Return loss in decibels as shown in Fig. 18 is displayed in network analyser with the help of above steps.

5. CONCLUSION

The proposed hook shaped aperture coupled circularly polarized antenna is fabricated on an FR4 substrate of thickness 2 mm and is designed with aperture coupling feeding. The aperture design is located on top of the substrate, and it consists of four hooks perpendicular to each other out of which one hook-shaped aperture radius is less than other, so circular polarization is achieved. Parametric analysis is carried out, and surface current is shown for the proposed antenna. For the novel hook shaped aperture coupled circularly polarized antenna, satisfactory impedance bandwidth and axial ratio are obtained with the usage of foam in between the substrate and patch, with the connectivity of shorting pin from the edge of the feed line to the patch. The performance parameters of the designed antenna are impedance bandwidth of 29.10%, axial ratio bandwidth of 13.47%, and gain of 4.08 dBic at the resonant frequency 3.47 GHz which falls in the 5G radio band. These performance characteristics of hook shaped aperture coupled circularly polarized antenna show enhancement in the bandwidth of impedance and axial ratio, and the simulated results are in good agreement with the measured ones.

ACKNOWLEDGMENT

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