



# A Wideband Circularly Polarized Antenna Using Substrate Integrated Waveguide and Truncated-Corner Patch Loaded Slot

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## Abstract

A wideband circularly polarized antenna based on the substrate integrated waveguide (SIW) is investigated and presented for mobile satellite applications. Initially, a rectangular-slot is etched on the top layer of the SIW cavity. A truncated patch from the one corner (top left) is loaded inside the slot to obtain the two pairs of orthogonal degenerate modes  $TE_{130}/TE_{310}$  and  $TE_{230}/TE_{320}$ . This truncated-corner patch helps to bring the orthogonal modes closer to obtain the wideband circular polarization. Further, a rotated rectangular-slot is incorporated inside the patch to enhance the circular polarization bandwidth. The antenna exhibits a relative impedance bandwidth of 20% (10.87–3.275 GHz) and an axial ratio bandwidth 11.50–12.26 GHz (6.4%). The broadside radiation characteristics are achieved with the peak gain of 6.3dBic and 7.0dBic at the two working frequencies 11.5 GHz and 12.0 GHz respectively.

**Keywords** Cavity-backed antenna · Circularly polarized · Patch antenna · Substrate integrated waveguide antenna · Wideband antenna

## 1 Introduction

Mobile satellite communication services are rapidly increasing with the growing need for communication in vehicles on land, water, and air. The antennas placed on these vehicles must have wide bandwidth, sufficient gain, should be lightweight and compact to provide reliable communication linkages [1]. Circularly polarized (CP) antennas can minimize the polarization mismatch caused by moving vehicles, allowing data to be sent regardless of the transmitter and receiver's orientation [2, 3]. Also, these CP antennas give good performance in bad weather environments.

The substrate integrated waveguide (SIW) cavity-backed CP antennas are appealing options as they can achieve enhanced gain, high power-handling capacity, low radiation loss, and smaller size than standard microstrip antennas [4–7]. The CP radiation can be

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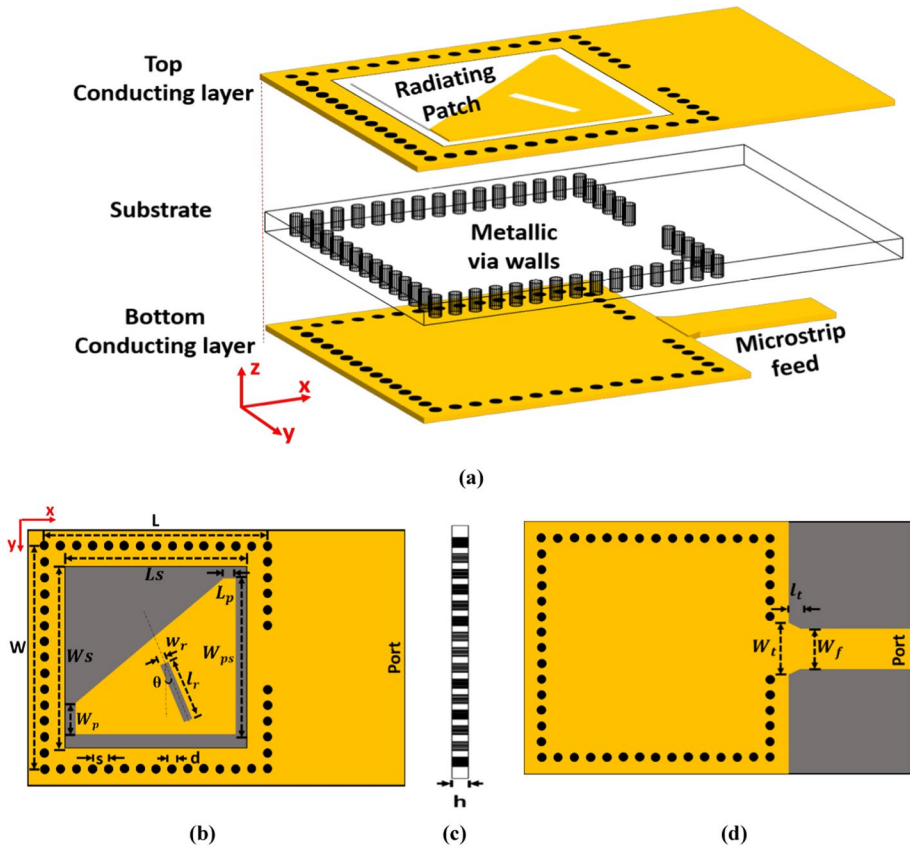
achieved by exciting the equal amplitude orthogonal degenerate modes with a  $90^\circ$  time phase difference [8]. Many studies on CP antennas using SIW are currently available for satellite communications and other wireless applications. In [9], crossed slots are etched inside the circular cavity to achieve 2.4% impedance bandwidth (IBW) and 0.6% axial ratio bandwidth (ARBW). In [10], a square annular ring slot is etched inside the SIW cavity with a shorting via to achieve IBW of 10.3% and ARBW of 2.6%. A circular truncated patch loaded circular slot is etched inside SIW cavity to achieve wide IBW [11]. In [12], a spoon-shaped slot is utilized to accomplish 6.3% IBW and 1.8% ARBW. In [13], a circular annular ring slot is incorporated inside the SIW cavity to achieve 6.13% IBW and 6.0% ARBW. Further in [14], triangular ring slots are utilized to achieve 1.4% IBW and 5.9% ARBW. In [15], a circular patch with uneven inductive via arrays are utilized to enhance the IBW to 18% but ARBW is reported 2.8%. In [16], two orthogonal split-ring resonators are utilized to achieve 10.8% IBW and 1.5% ARBW. In most of the aforementioned antennas, wide IBW is achieved, however, the ARBW is narrow. Therefore, the primary design challenge is to improve the ARBW along with the IBW. The SIW cavity that resonates on higher-order modes gives the advantage of enhanced gain at higher frequency [17]. This characteristic can be utilized in the design of a high gain antenna at high frequencies.

In this paper, a wideband CP antenna based on dual orthogonal modes is proposed. The novelty of the antenna lies in the utilization of dual higher-order orthogonal modes ( $TE_{130}$  and  $TE_{310}$ ) and ( $TE_{230}$  and  $TE_{320}$ ), for the wideband CP operation with enhanced gain. The CP operation using the degenerate orthogonal modes is achieved by truncating a single corner of the square-shaped patch loaded in the square-shaped slot on the top layer of the SIW cavity. The amount of truncation influences the impedance match and affects the axial ratio bandwidth. An additional rectangular slot is loaded inside the patch for further improvement in CP bandwidth. The antenna is designed using the full-wave EM simulation software (CST Microwave Studio) and fabricated with LPKF machine. The proposed antenna's mechanism and practicality are confirmed by a good agreement in the simulated and experimental results. The manuscript is organized as follows: Section II explains the design configuration and mode analysis followed by the simulated results. The fabrication and performance comparison between the measured and simulated results is presented in section III. Finally, section IV concludes the paper.

## 2 Antenna Design and Analysis

### 2.1 Antenna Configuration

The design of the proposed CP antenna is shown in Fig. 1a, b, c and d. It comprises an RT/Duriod 5870 substrate (thickness 1.57 mm and  $\epsilon_r = 2.33$ ,  $\tan\delta_e = 0.0012$ ). The top and bottom metallic layers of the substrate are connected through the shorting vias to form the SIW cavity structure. The diameter and spacing between consecutive vias are kept according to the predefined rules [18] for minimum leakage losses. A  $50\Omega$  microstrip feedline with tapered transition is utilized to excite the SIW cavity structure. A rectangular slot is etched on the top of the substrate to reduce the practical electrical dimensions of the cavity. A square patch truncated from one corner is placed inside the slot. The length of the truncated sides of the patch is kept different. This arrangement helps in exciting a pair of orthogonal degenerate modes in the SIW cavity. A rectangular slot is loaded inside the truncated patch for further enhancement of the ARBW.



**Fig. 1** Layout of CP antenna **a** Exploded view **b** Top view, **c** Side view, and **d** Bottom view

The design evolution of the proposed antenna is presented in Fig. 2. It begins with analyzing the pair of orthogonal modes for circular polarization at two distinct frequencies. Therefore, the Eigen mode analysis is performed in the SIW cavity. Figure 2a depicts the low frequency (LF) modes  $TE_{130}/TE_{310}$  at 11.3 GHz and the high frequency (HF) modes  $TE_{230}/TE_{320}$  at 12.2 GHz existing inside the square shape SIW cavity structure. A single square ring shaped slot having an outer side length of 23.0 mm, and the inner side length of 19.7 mm is etched at the center of the top layer in the SIW cavity as shown in Fig. 2b. The slot length is derived from Eq. (1) of conventional square ring slot antennas [24]:

$$f_l = \frac{c}{2 * (x_1 + x_2)} \left( 3 \sqrt{\frac{\epsilon_{reff} + 1}{2\epsilon_{reff}}} \right) \quad (1)$$

where 'c' is the speed of light in free space and 'f<sub>l</sub>' is the fundamental resonant frequency of the conventional square ring slot antennas. The dimensions of the slot are chosen to excite the orthogonal modes of the SIW cavity (Fig. 2b). The antenna is fed from the bottom using a tapered microstrip feedline of 50Ω. This arrangement of antenna exhibits wide bandwidth but with linear polarization. Further, for obtaining the circular polarization the, square patch is truncated asymmetrically from one corner (Fig. 2c). The asymmetric

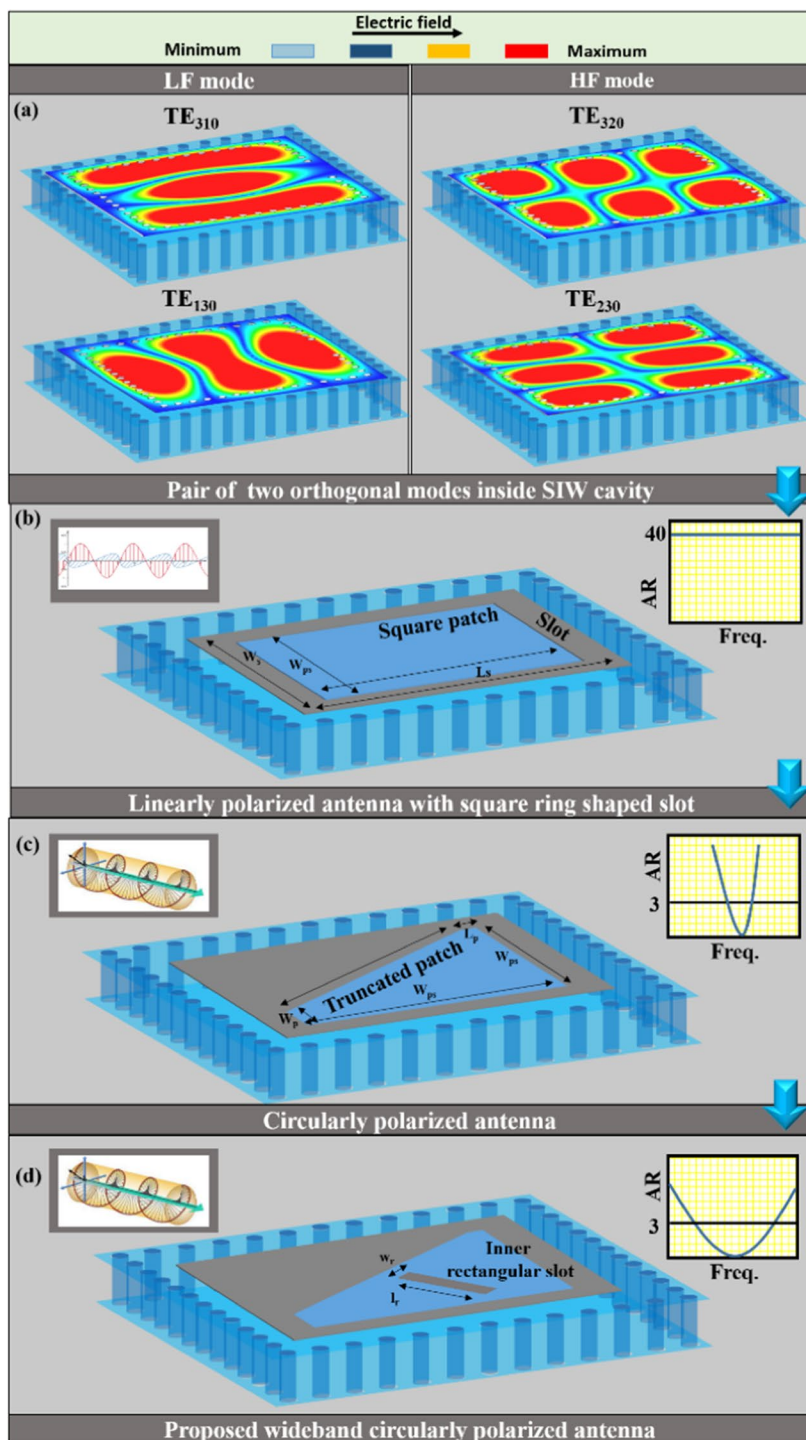
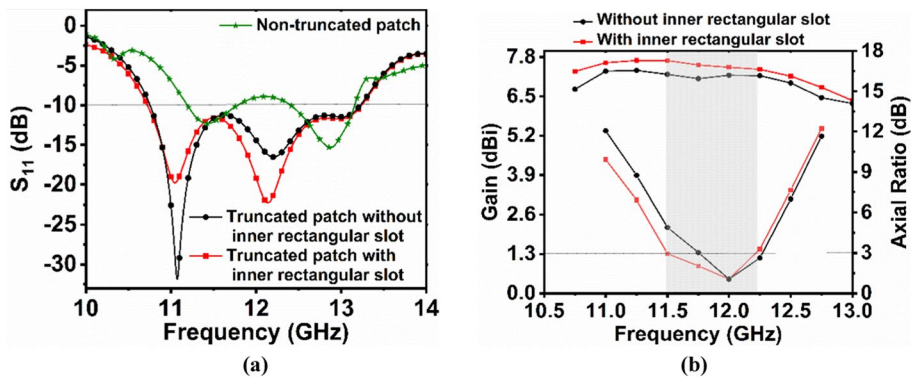


Fig. 2 Design advancement of the truncated patch circularly polarized antenna



**Fig. 3** Comparison between the  $S_{11}$ , Axial Ratio, and Gain of the antenna (without and with) truncated patch and (without and with) inner rectangular slot

truncation of the corner of the patch forms unequal lengths of the patch edges  $L_p$  and  $W_p$ . By properly choosing the length of edges of the truncated-corner patch, the equal magnitude of the degenerate orthogonal modes, and the time phase difference of  $90^\circ$  at two closely spaced frequencies is achieved. Thus, circular polarization is achieved by the chosen truncation lengths. The fundamental resonance mode for circular polarization occurs at the frequency:

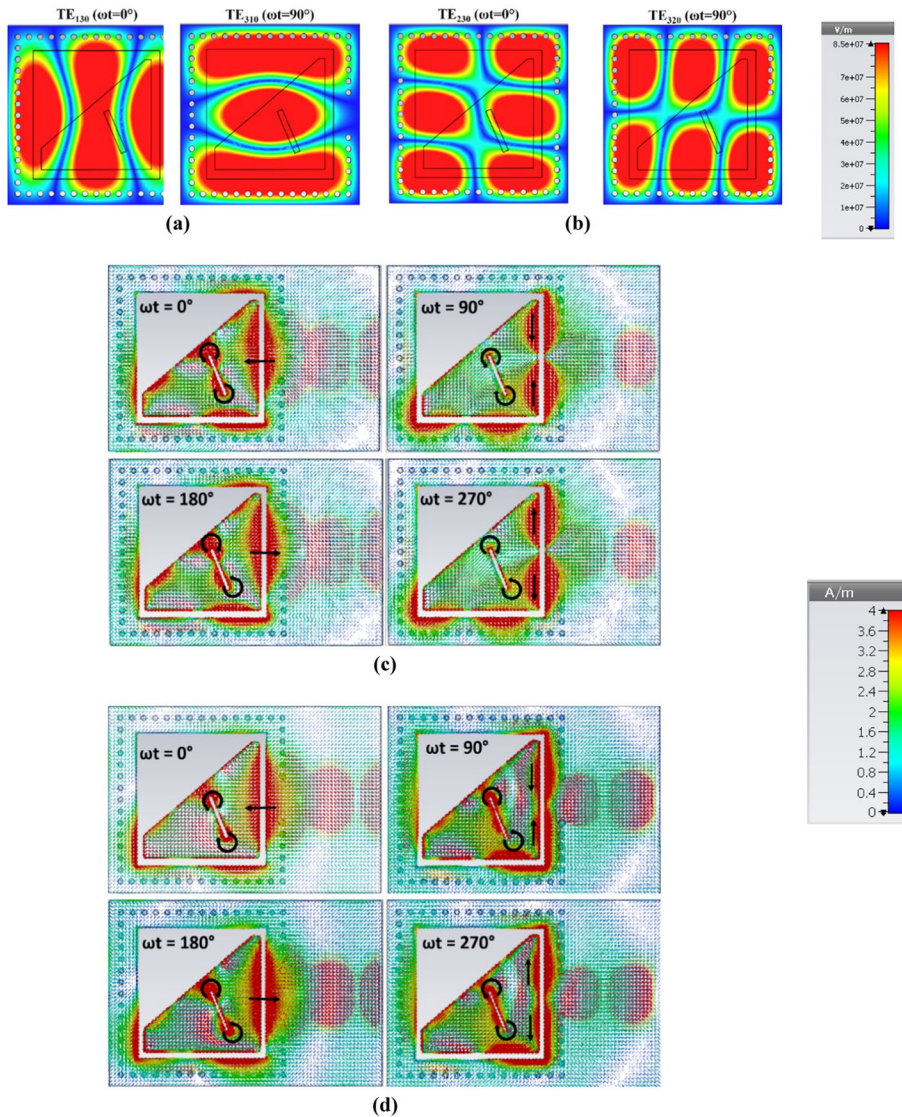
$$f_{lcp} = \frac{c}{(W_p + W_{ps})} * \text{correctionfactor} \quad (2)$$

$$f_{hcp} = \frac{c}{(L_p + L_{ps})} * \text{correctionfactor} \quad (3)$$

where  $\text{correctionfactor} = \sqrt{\frac{1+\epsilon_{\text{reff}}}{2*\epsilon_{\text{reff}}}}$ .

The ARBW of the antenna is enhanced by loading a rectangular-shaped slot inside the truncated patch (Fig. 2d). The length of the slot is kept approximately equal to half the guided wavelength ( $\lambda_g/2$ ). The dimensions of the proposed CP antenna are  $L=28$  mm,  $s=2$  mm,  $d=1$  mm,  $W=28$  mm,  $L_s=22.6$  mm,  $W_s=23$  mm,  $W_{ps}=19.7$  mm,  $W_p=3.5$  mm,  $L_p=0.98$  mm,  $W_t=6.6$  mm,  $l_t=1.5$  mm,  $W_f=4.7$  mm,  $l_f=8$  mm,  $w_f=1$  mm,  $\theta=22.5^\circ$ .

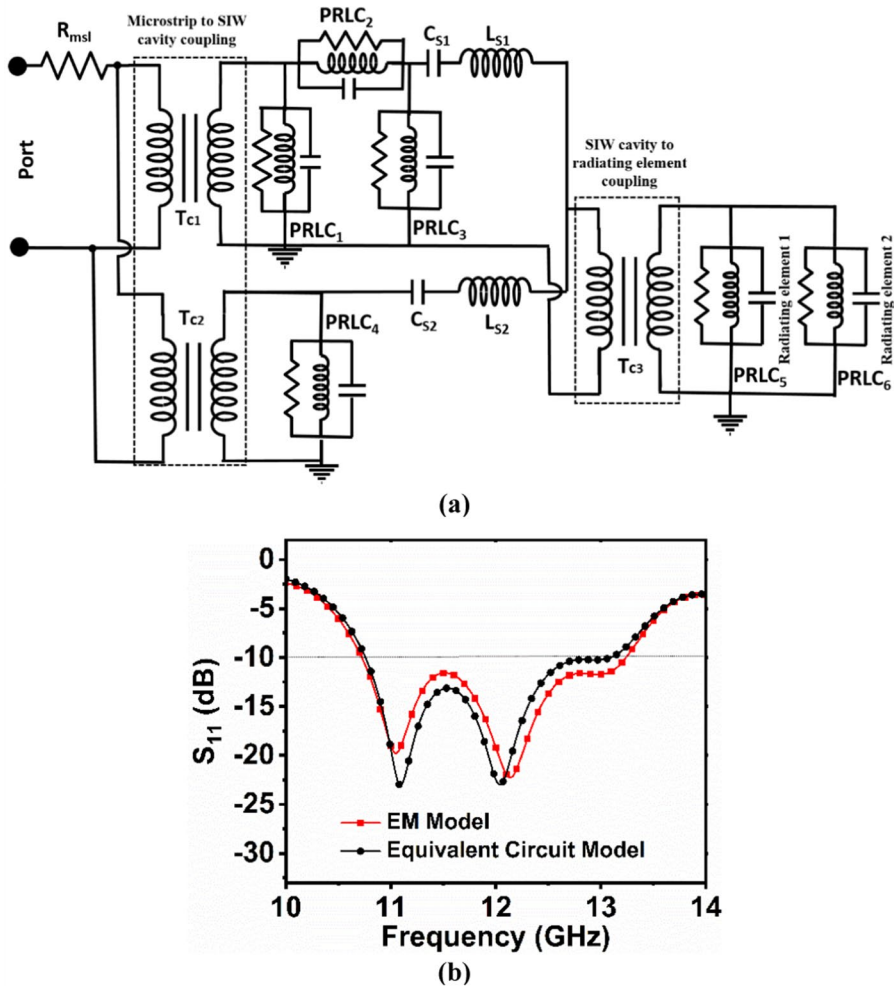
Figure 3 shows a comparison of the  $S_{11}$  of the antennas without truncated patch, with truncated patch (without inner rectangular slot), and with the truncated patch (with inner rectangular slot) along with a comparison of the axial ratios of the proposed antenna with and without an inner rectangular slot. It can be observed from Fig. 3a that the antenna without truncation resonates at two frequencies with orthogonal modes but depicts dual-band behavior instead of a wideband behavior. Further, on truncating the square patch from one corner, the two resonances come closer thereby enhancing the impedance bandwidth. However, much difference is not observed between the  $S_{11}$  response of truncated patch with and without the inner rectangular slot. It should be noted that the antenna without truncation exhibits a linearly polarized behavior while on the other hand, the truncation at the corner of the patch introduces circular polarization. From Fig. 3b a significant difference between the axial ratio, and gain can be observed for the antenna without inner rectangular slot and



**Fig. 4** Electric field distribution at **a** 11.5 GHz, **b** 12.0 GHz; Surface current distribution at **c** 11.5 GHz, and **d** 12.0 GHz

with inner rectangular slot. The inner rectangular slot improves both the axial ratio and the gain. The axial ratio bandwidth gets enhanced from 0.5 GHz (11.760–12.265 GHz) to 0.734 GHz (11.499–12.225 GHz) and gain increases from 7.21dBi to 7.59dBi at 12 GHz. Thus, in the production of CP radiation, the key parameters are the asymmetric length of truncation at the corner and the dimensions of the inner rectangular slot.

The electric field distribution of the SIW-based antenna at 11.5 GHz and 12.0 GHz with time phase  $\omega t = 0^\circ$  and  $90^\circ$  is shown in Fig. 4a and b. The asymmetric truncation of the square patch excites the two pairs of orthogonal modes ( $TE_{130}/TE_{310}$  and  $TE_{320}/TE_{230}$ )



**Fig. 5** **a** Equivalent circuit model of the proposed CP antenna, and **b** Comparison between the  $S_{11}$  of the EM model and ECM model of the antenna

with  $90^\circ$  time phase difference. The enhancement of ARBW by loading the inner rectangular slot is confirmed by the progressive variation of the surface current. The surface current distribution at different phase intervals ( $\omega t = 0^\circ, 90^\circ, 180^\circ$ , and  $270^\circ$ ) is observed at 11.5 GHz and 12.0 GHz and shown in Fig. 4c and d, respectively. The rotation of surface current in counter-clockwise direction at both the frequencies confirms that the antenna is right-hand circularly polarized (RHCP) in the broadside direction.

## 2.2 Equivalent circuit Model

To get a clear understanding of the impedance matching, an equivalent circuit model (ECM) of the proposed antenna is developed and shown in Fig. 5a. It comprises three

sections coupled together: Microstrip feed, SIW cavity, and the radiating elements. The coupling elements  $T_{C1}$  and  $T_{C2}$  couples the microstrip feed line to the SIW cavity. The parallel RLC components  $PRLC_1$ ,  $PRLC_2$ ,  $PRLC_3$ , and  $PRLC_4$  corresponds to the two orthogonal degenerate modes and one non degenerate higher order mode of the SIW cavity. The SIW cavity modes are coupled to the radiating elements by the coupling element  $T_{C3}$ . The radiating elements of the antenna are also modeled as parallel RLC components  $PRLC_5$  and  $PRLC_6$  where the  $PRLC_5$  is for the outer rectangular slot and the truncated patch and  $PRLC_6$  are for the inner rectangular slot. The component values of the equivalent circuit are given in Table 1. The equivalent circuit is modeled and simulated on the Keysight ADS simulation software. A good agreement between the s-parameters acquired from Electromagnetic Model (EM) using CST Studio Suite and Equivalent Circuit Model (ECM) using ADS can be observed in Fig. 5b.

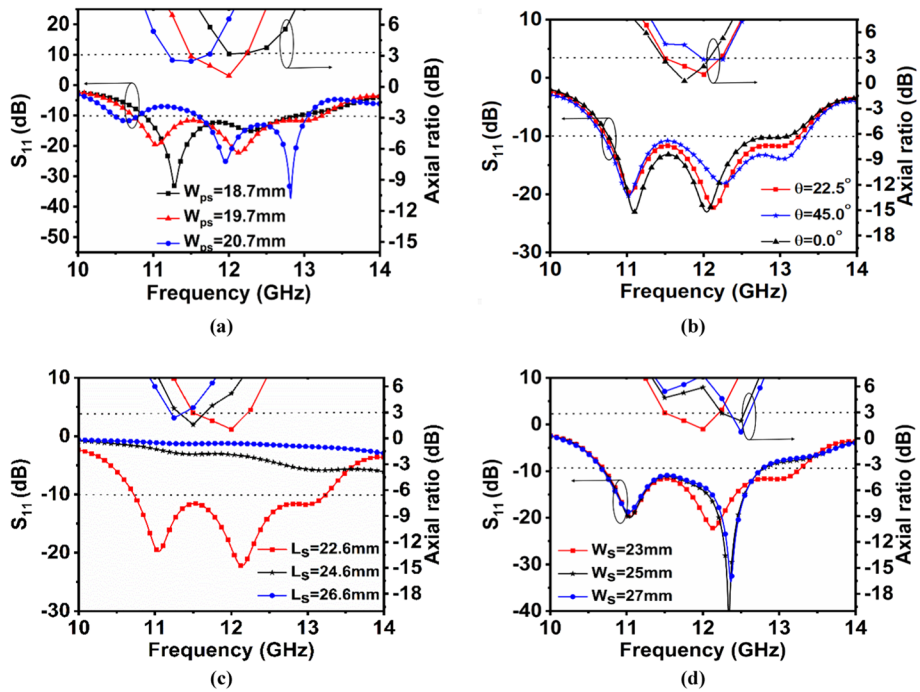
## 2.3 Parametric Study

The dependency of antenna performance on the geometrical parameters is studied in simulation by parametric variation. In Fig. 6a, when  $W_{ps}$  (width of the square patch) changes from 20.7 to 18.7 mm, the resonance frequencies gradually move toward the higher frequency. It is because the size of the patch reduces. At 19.7 mm maximum impedance matching yields maximum ARBW and IBW. However, no specific change occurs in the ARBW and IBW on varying the truncation lengths  $L_p$  and  $W_p$  in small intervals. The effect of variation of the length of the truncated patch is also analyzed utilizing the equivalent circuit model. Table 2 shows that the change in length of the truncated patch is controlled by the radiating element 1 of the ECM model. The increase in the values of geometrical parameter  $W_{ps}$  is equivalent to the corresponding increase in the values of ( $R_5$  and  $L_5$ ) and ( $R_5$  and  $C_5$ ) while fixing the values of  $C_5$  and  $L_5$ , respectively. The effect of rotation of the inner rectangular slot is shown in Fig. 6b. This rotation is modeled in the ECM by radiating element 2 ( $R_6$ ) and is shown in Table 3. The variation in rotation angle directly affects the coupling between the SIW and the radiating slot. Thus with the increase in the rotation angle, the impedance matching is reduced and the overall impedance bandwidth is enhanced. However, maximum ARBW is obtained at a rotation angle of  $22.5^\circ$ .

The effect of variation of the dimensions ( $W_s$ ,  $L_s$ ) of the outer rectangular slot is shown in Fig. 6c and d. With the increase in the length ( $L_s$ ) of the slot, the two orthogonal modes are disturbed and the IBW is entirely lost. At  $L_s = 22.6$  mm, maximum ARBW and IBW are obtained. Table 4 portrays a similar effect by varying the values of  $R_3$  in the ECM. An increase in the values of  $L_s$  is modeled by the corresponding increase in the  $R_3$  values

**Table 1** Equivalent circuit components values of the proposed SIW based CP antenna

| Component | Value          | Component | Value           | Component | Value           |
|-----------|----------------|-----------|-----------------|-----------|-----------------|
| $T_{C1}$  | 1.79           | $PRLC_2$  | 0.2 K $\Omega$  | $PRLC_4$  | 5.17 K $\Omega$ |
| $T_{C2}$  | 1.79           |           | 0.78 nH         |           | 1.23 nH         |
| $T_{C3}$  | 1.96           |           | 0.26 pF         |           | 0.70 pF         |
| $PRLC_1$  | 5.78K $\Omega$ | $PRLC_3$  | 1.02 K $\Omega$ | $PRLC_5$  | 3.04 K $\Omega$ |
|           | 0.22nH         |           | 0.68 nH         |           | 0.48 nH         |
|           | 0.66pF         |           | 0.67 pF         |           | 0.52 pF         |
| $L_{S1}$  | 1.68nH         | $L_{S2}$  | 0.35 nH         | $PRLC_6$  | 6.04 K $\Omega$ |
| $C_{S1}$  | 0.36pF         | $C_{S2}$  | 0.36 pF         |           | 1.48 nH         |
| $R_{msl}$ | 22.6 $\Omega$  |           |                 |           | 0.63 pF         |



**Fig. 6** Parametric variation **a** patch width, **b** rotation angle, **c**, **d** outer rectangular-slot dimensions

**Table 2** Effect of variation truncated patch length ' $W_{ps}$ '

| Resonant frequency (GHz) | Circuit model                 |            |                               |            | CST                                 |
|--------------------------|-------------------------------|------------|-------------------------------|------------|-------------------------------------|
|                          | $C_5 = 0.52\text{pF}$ (Fixed) |            | $L_5 = 0.48\text{nH}$ (Fixed) |            | Geometrical parameter $W_{ps}$ (mm) |
|                          | $R_5$ (K $\Omega$ )           | $L_5$ (nH) | $R_5$ (K $\Omega$ )           | $C_5$ (pF) |                                     |
| 11.2, 12.3               | 1.96                          | 0.36       | 1.96                          | 0.33       | 18.7                                |
| 11.0, 12.1               | 3.04                          | 0.48       | 3.04                          | 0.52       | 19.7                                |
| 10.7, 11.9               | 4.73                          | 0.59       | 4.73                          | 0.68       | 20.7                                |

**Table 3** Effect of variation of rotation angle ' $\theta$ ' of inner rectangular slot

| Circuit model       | CST                                      | IBW (GHz)   |
|---------------------|------------------------------------------|-------------|
| $R_6$ (K $\Omega$ ) | Geometrical parameter $\theta$ (degrees) |             |
| 4.98                | 0                                        | 10.87–13.27 |
| 6.04                | 22.5                                     | 10.90–12.82 |
| 7.76                | 45.0                                     | 10.75–13.35 |

**Table 4** Effect of variation of slot length 'Ls'

| Circuit model                                         | CST                           |
|-------------------------------------------------------|-------------------------------|
| $L_3 = 0.68\text{nH}$ , $C_3 = 0.67\text{pF}$ (Fixed) |                               |
| $R_3$ (K $\Omega$ )                                   | Geometrical parameter Ls (mm) |
| 1.02                                                  | 22.6                          |
| 0.87                                                  | 24.6                          |
| 0.63                                                  | 26.6                          |

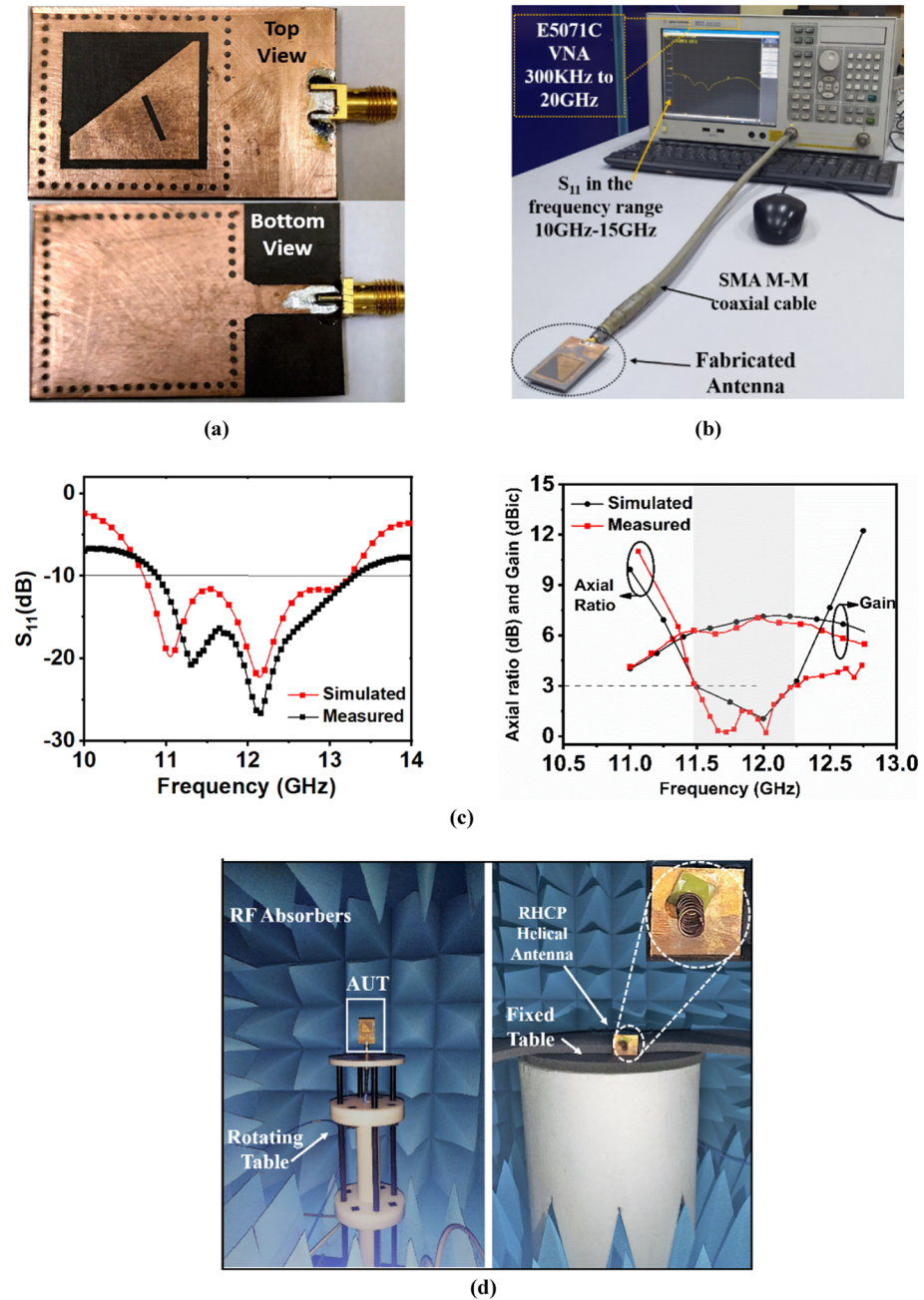
thereby leading to poor impedance matching. Further, on varying the width ( $W_s$ ) of the slot the ARBW gets altered with a small shift in higher resonance frequency. This effect is analyzed in ECM model by linearly varying the values of  $L_3$  and  $C_3$  individually keeping the either one fixed. Table 5 depicts the effect of variation of  $W_s$  on both EM model and ECM model.

### 3 Fabrication and Measurement

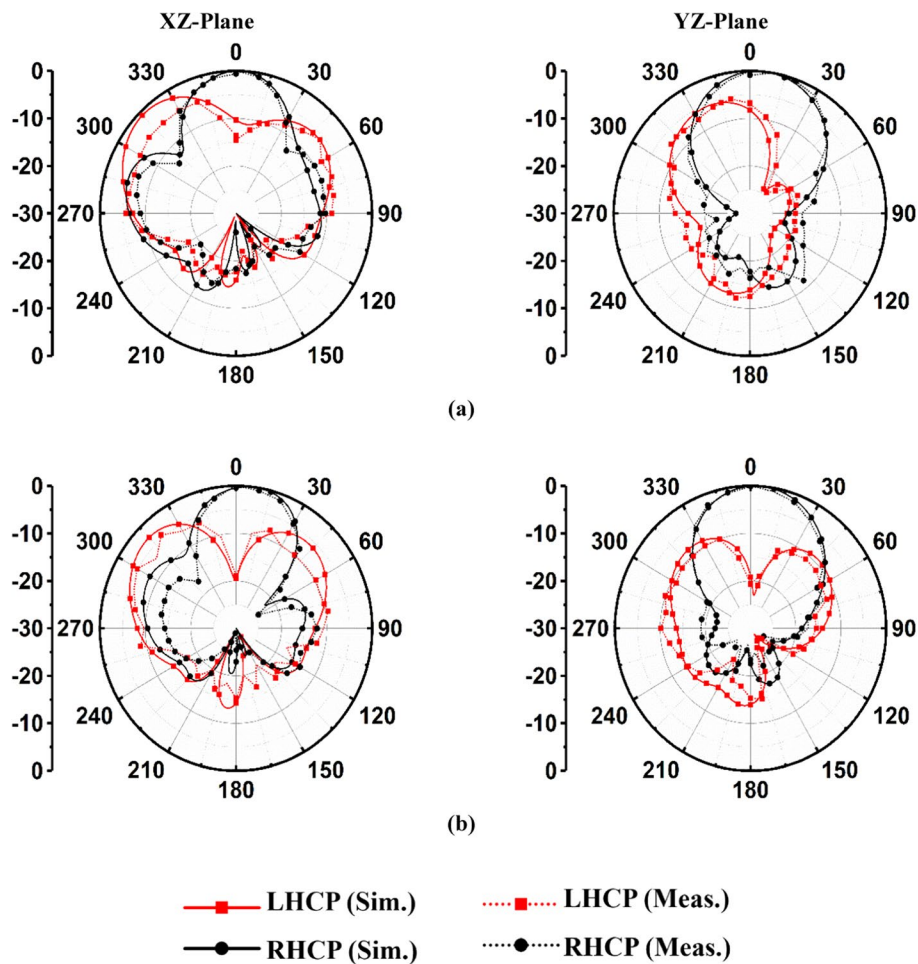
A prototype of the proposed CP antenna is fabricated and tested using a vector network analyzer E5071C as shown in Fig. 7a and b. The comparison between the measured and simulated reflection coefficients along with the axial ratios is shown in Fig. 7c. The measured reflection coefficient achieves  $-10$  dB bandwidth covering 10.870–13.275 GHz (20%). The measured ARBW ranges from 11.50 to 12.26 GHz (6.4%). The far-field radiation of the CP antenna is measured in an anechoic chamber as shown in Fig. 7d. The LHCP/RHCP radiation is measured by keeping the AUT and LHCP/RHCP helical antenna in the same plane and rotating the AUT with steps of  $10^\circ$ . Figure 8 shows a comparison between the simulated and measured radiation patterns in both xz-plane and yz-plane at both frequencies. The gain of the CP antenna is illustrated in Fig. 7c. At 11.5 GHz the gain is 6.3dBic and at 12.0 GHz the gain is 7.0dBic. A comparison of the proposed work with recently reported similar works is illustrated in Table 6. It can be observed that the proposed low-profile antenna exhibits a wide ARBW and IBW along with enhanced gain.

**Table 5** Effect of variation of slot length 'Ws'

| Resonant frequency (GHz) | Corresponding change in $S_{11}$ (dB) | Circuit model                 |                               | CST                              |
|--------------------------|---------------------------------------|-------------------------------|-------------------------------|----------------------------------|
|                          |                                       | $C_3 = 0.67\text{pF}$ (Fixed) | $L_3 = 0.68\text{nH}$ (Fixed) |                                  |
|                          |                                       | $L_3$ (nH)                    | $C_3$ (pF)                    | Geometrical parameter $W_s$ (mm) |
| 12.1                     | -24                                   | 0.680                         | 0.67                          | 23                               |
| 12.35                    | -40                                   | 0.650                         | 0.64                          | 25                               |
| 12.4                     | -32                                   | 0.615                         | 0.60                          | 27                               |



**Fig. 7** **a** Fabricated antenna, **b**  $S_{11}$  measurement, **c** Simulated and measured  $S_{11}$ , Axial ratio and Gain, **d** Far-field pattern measurement



**Fig. 8** Simulated and measured radiation patterns at **a** 11.5 GHz, **b** 12.0 GHz

**Table 6** Comparative performance analysis of SIW based CP antennas

| References | Freq.(GHz) | IBW (%) | ARBW (%) | Gain (dBic) | Size                                 | Modes                                                                       |
|------------|------------|---------|----------|-------------|--------------------------------------|-----------------------------------------------------------------------------|
| [15]       | 10.20      | 17.3    | 2.3      | 7.7         | $1.5\lambda_0 * 1.16\lambda_0$       | TM <sub>11</sub>                                                            |
| [19]       | 10.47      | 23.9    | 2.7      | 6.6         | $1.5\lambda_0 * 0.86\lambda_0$       | TM <sub>11</sub>                                                            |
| [20]       | 12.24      | 4.2     | 1.6      | 7.0         | $0.92\lambda_0 \times 0.90\lambda_0$ | TE <sub>202</sub>                                                           |
| [21]       | 5.78       | 2.4     | 0.7      | 10.4        | $1.31\lambda_0 * 1.31\lambda_0$      | N.R                                                                         |
| [22]       | 28         | 3.7     | 1.2      | 6.89        | $3.8\lambda_0 * 1.9\lambda_0$        | TM <sub>210</sub>                                                           |
| [23]       | 5.03       | 7.2     | 3.9      | 8.0         | $1.01\lambda_0 * 1.01\lambda_0$      | TE <sub>102</sub> /TE <sub>201</sub>                                        |
| [24]       | 10.78      | N.R     | 0.74     | 12.2        | $3.77\lambda_0 * 3.5\lambda_0$       | TE <sub>430</sub> /TE <sub>340</sub>                                        |
| This work  | 11.5, 12.0 | 20.0    | 6.4      | 6.3, 7.0    | $1.07\lambda_0 * 1.07\lambda_0$      | TE <sub>130</sub> /TE <sub>310</sub> , TE <sub>230</sub> /TE <sub>320</sub> |

## 4 Conclusion

A SIW based wideband circularly polarized unidirectional antenna is designed, fabricated, and tested for satellite communications. The main contribution of this work lies in utilizing two pairs of higher-order orthogonal modes in SIW cavity for achieving wide bandwidth and enhanced gain. A square patch truncated from one corner and a rotated rectangular-slot, helps in bringing the two pairs of orthogonal modes closer for circular polarization. The optimum amount of truncation helps in achieving the wideband CP radiation. The designed antenna is producing the gain of 6.3dBic and 7.0dBic at 11.5 GHz and 12.0 GHz, respectively. The ARBW of 6.4% (11.50–12.26 GHz) and radiation pattern with a good FTBR (> 20 dB) is achieved in the broadside direction.

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**Data Availability** Data sharing does not apply to this article as no datasets were generated or analyzed during the current study.

## Declarations

**Conflict of interest** The author declares no potential conflict of interest.

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