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A low-profile triple-band circularly polarized wide slot antenna for wireless systems

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Abstract

A simple design for triple-band circularly polarized (CP) wide slot antennas is proposed and experimentally investigated. The proposed antenna having a microstrip-fed rectangular patch with *T*-shaped notch for triple-band operation and a modified wide square slot on ground plane for CP operation. The measured 10 dB reflection bandwidths are 1.24% (≈340 MHz from 2.56 to 2.9 GHz), 9.63% (≈430 MHz from 4.25 to 4.68 GHz), and 5.34% (≈490 MHz from 8.93 to 9.42 GHz). The generated 3 dB axial ratio bandwidths of the proposed antenna are 7.54, 8.98, and 1.65% at operating frequencies around 2.65, 4.45, and 9.09 GHz, respectively. The measured peak gains within the 3 dB axial ratio bands are 3.03, 3.5, and 5.64 dBi. The simulated and measured results for the return loss, axial ratio, and antenna gain show a good agreement, which validate the antenna design.

Introduction

Numerous wireless systems operate at several different frequency bands. For example, satellite system and modern GNSS systems employ signals at several frequency bands. For these systems, it is possible to utilize a few single-band circularly polarized antennas, with one antenna covering each frequency band independently. This, in any case, will prompt a large size, weight, and high cost of antenna and wireless systems. It is much more attractive if a single multi-band CP antenna can be employed for these applications, as it can result in a significant reduction in size, weight, cost, and complexity of wireless systems. The basic benefits of circular polarization are its high penetration capability compared with linear polarization and its ability of creating a reliable signal link irrespective of the antenna orientation of the device. The CP wave acquires two degenerated orthogonal modes with different resonant frequencies and there is a phase difference of 90° between two orthogonal modes.

Multi-band antenna with circular polarization plays an important role in wireless and satellite communication area because they can be used to reduce the loss of polarization mismatch and cover operation frequencies of various wireless communication systems. Thus, multi-band CP antennas have become a hot research topic in recent decades and a variety of techniques have been developed. There are different techniques for designing multi-band CP antennas, including multi-band CP microstrip patch antennas, multi-band CP slot antennas, multi-band CP DRAs, multi-band CP loop antenna [1–8], and so on. Multi-band CP antennas can be obtained by utilizing the stacked patch arrangement. Multi-band CP antennas can be realized by using single-feed or multi-feed patches. The use of multi-feed patches can suppress undesired higher order modes and has higher polarization purity and broad bandwidth. But due to the expense of complicated feed network and a large feed size, single-feed design has advantages of a simple feed structure, compact size, and low fabrication cost. Single-feed slot-loaded patches and the dual-loop antenna are attractive for dual-band CP operations due to their advantages of a simple structure and easy fabrication.

There were several methods available in open literature to achieve broadband, dual-band, and multi-band operation for microstrip antennas [9–16], because of their low profile with simple structure. Moreover, by specially designing of a microstrip line-fed wide-slot antenna, they can produce multiple operating frequency bands and CP radiation. Several technologies have been proposed to produce circular polarization [17–22], all these designs only realize CP radiation at a single frequency. However, relatively few designs of dual-frequency slot antenna with dual orthogonal circular polarization have been reported in [23–25]. In [26], asymmetric slits loaded irregular-shaped microstrip patch antenna with good triple-band CP radiation characteristics. Further antennas with various shapes of microstrip feed line and rectangular wide slot have been introduced for triple impedance bandwidths with CP radiations [27–31]. A single-feed tri-band CP annular slot antenna is designed to operate at the L1 and L2 bands that are presented in [27]. Paper [28] reported a novel design of a CP antenna for

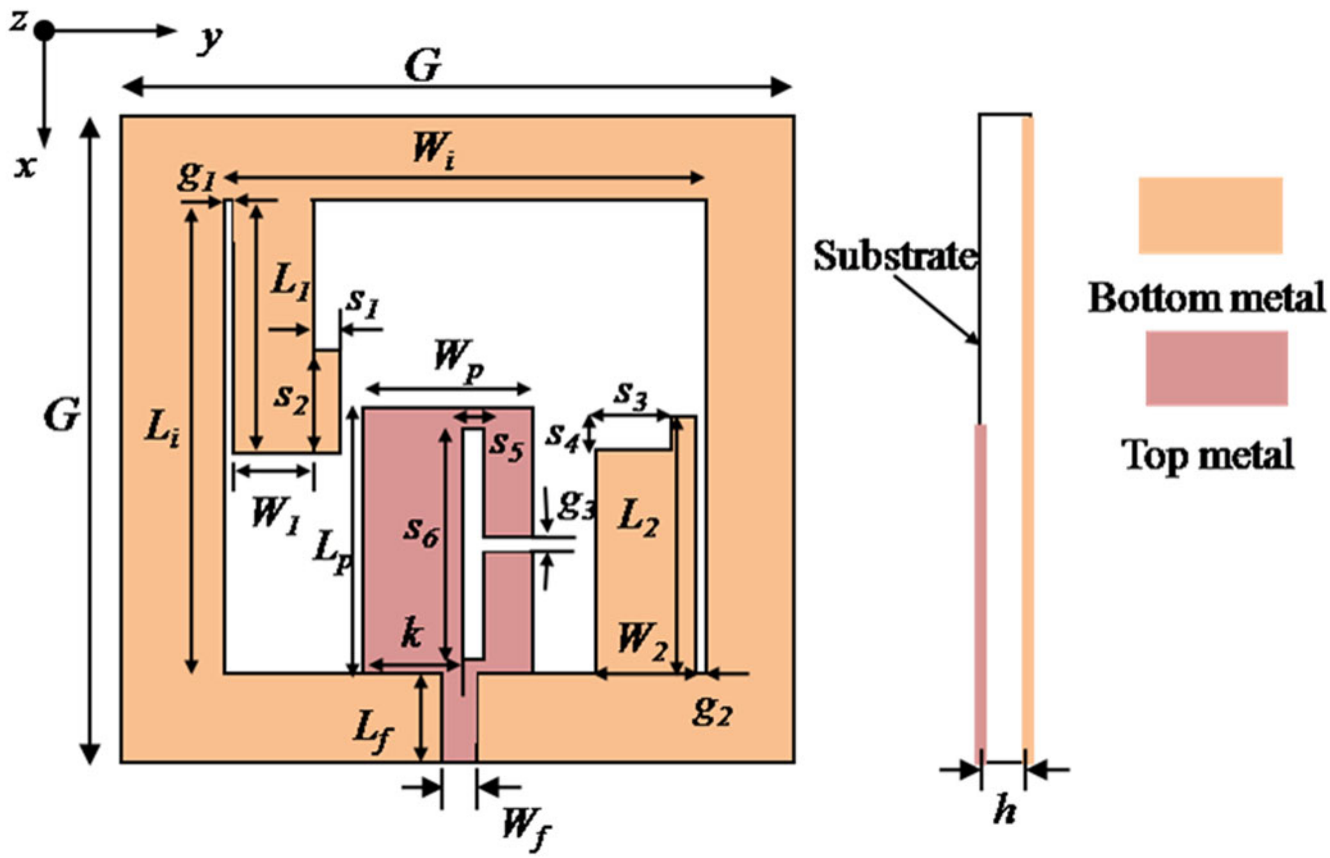

Fig. 1. Geometry of proposed antenna: (a) top view and (b) side view.

multiband GPS receivers. The design of a triple-band CP hexagonal slot antenna with *L*-shaped slits is presented in [29]. A novel single-layer single-probe feed asymmetrical fractal boundary microstrip antenna is considered for tri-band CP operation [30]. The triple-band wide CP frequency ratio is achieved by appropriate adjustment of patch sizes as presented in [31].

This paper presents a novel low-profile triple-band CP wide slot antenna that utilizes a rectangular patch with *T*-shaped notch and asymmetric wide slot on the ground plane. Compared with the previous triple-band antenna design, the proposed antenna is easy to fabricate and has the flexibility to obtain arbitrary polarization at each frequency. A good triple impedance bandwidths and radiation characteristics can be achieved by proper designing of the proposed antenna for multi-band wireless communication systems.

Antenna structure and design

The proposed antenna has a simple structure. The proposed antenna featured for triple-band CP radiation characteristic has been simulated with high-frequency simulator software (HFSS 13.0). The analysis of some antenna prototypes is implemented, and simulated results are presented and discussed in this section.

Antenna configuration

The schematic configuration of the proposed microstrip line-fed wide slot antenna for triple-band CP operation is shown in Fig. 1. For the design studied here, the radiating patch with *T*-shaped notch and ground plane with a modified wide slot are etched on the opposite sides of a square FR4 substrate with a dielectric constant of 4.4 and a thickness of 1 mm. A *T*-shaped notch-loaded radiator is printed on the upper surface of the substrate and used to generate three resonance frequency bands. The *T*-shaped notch of parameters s_5, s_6, and g_3 etched on the right side of the radiating patch ($L_p \times W_p$) with 90° shift from *x*-direction. The modified wide slot-loaded ground is printed on the lower surface of the substrate. Two rectangular strips ($L_1 \times W_1$, $L_2 \times W_2$) are added at the opposite corner of the lower ground to produce CP waves with different polarization. To control the surface current distributions, a small rectangular strip ($s_1 \times s_2$) is added at the left side rectangular strip with gap g_1, and a small rectangular slit ($s_3 \times s_4$) is cut at the right side rectangular strip with gap g_2 from the ground frame.

The parameters for the proposed triple-band CP antenna are listed in Table 1.

Antenna prototypes

The antenna prototypes to realize the proposed antenna design is represented in Fig. 2. The overall volume G mm × G mm × h mm is constant across the design process of desired antenna. To explain the design process of this low-profile triple-band CP wide slot antenna clearly, four design steps are analyzed for the impedance bandwidth and axial ratio bandwidth (ARBW). Design 1 has only a straight *x*-axis-directed rectangular patch and a framed ($L_i \times W_i$) lower ground. Design 2 moves the rectangular patch to negative *y*-direction (k) and adding a horizontal *T*-shaped notch on the rectangular patch from *y*-direction. This is

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Table 1. Dimensions of the proposed antenna

Parameters	Unit (mm)	Parameters	Unit (mm)
G	40	L_i	30
W_i	30	L_1	16
W_1	5	l_2	15
W_2	6	L_p	16
W_p	11.5	L_f	5
W_f	2	s_1	1.5
g_1	0.5	s_2	7
g_2	0.5	s_3	5
g_3	1	s_4	2.5
k	6.5	s_5	1
h	1	s_6	14

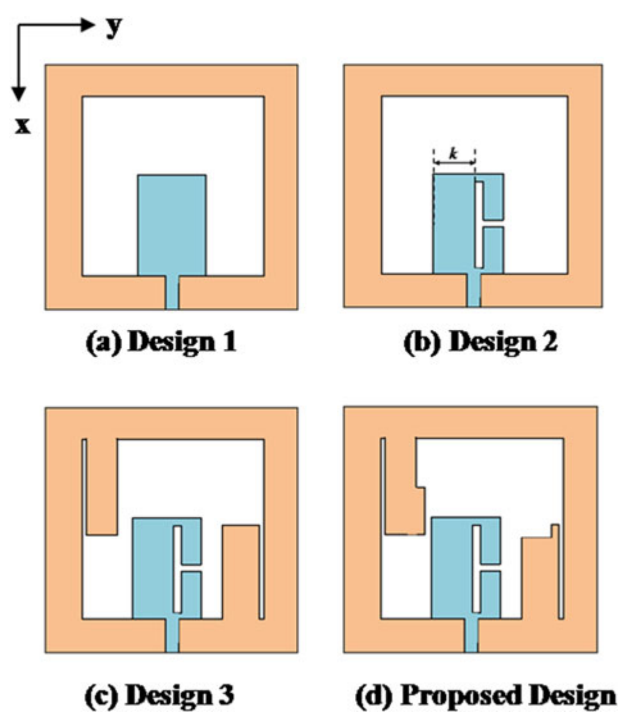

Fig. 2. Three improved prototypes with the proposed antenna.

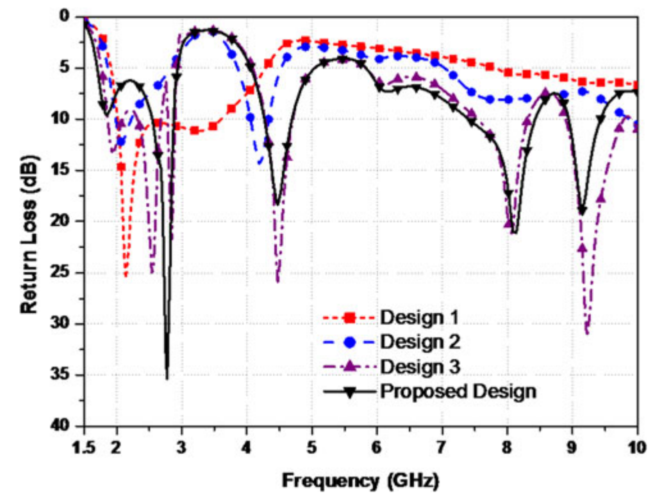

Fig. 3. Simulated results of return loss for three designs with the proposed design.

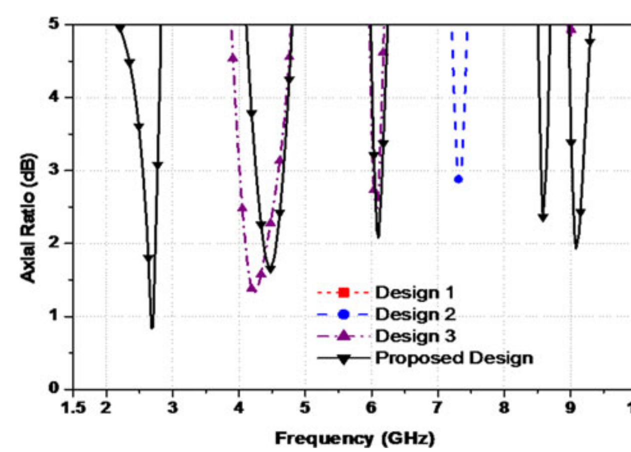

Fig. 4. Simulated results of axial ratio for three designs with the proposed design.

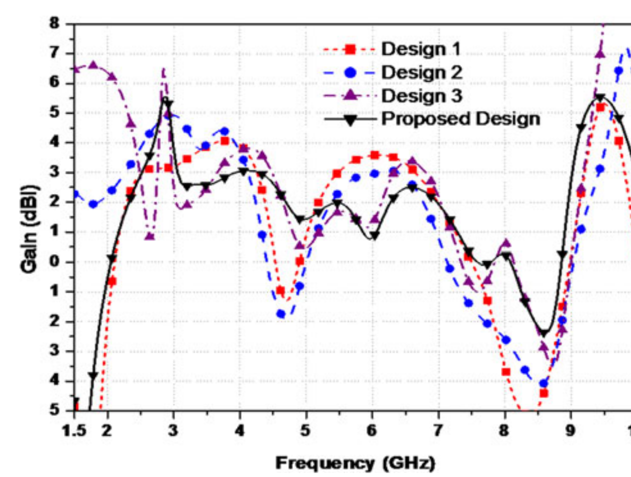

Fig. 5. Simulated results of gain for three designs with the proposed design.

a common method to achieve dual-band operation. Design 3 adds two opposite x-axis-directed strips on the ground frame for improving multiband operation with CP radiation. The proposed antenna is designed after introducing two main structures in design 3: one is the rectangular strip that is added on the x-axis-directed (left-sided) rectangular strip and the second is the rectangular slit that is cut on the negative x-axis-directed (right-sided) rectangular strip at lower ground frame.

Design simulation

Simulated results of all three prototypes with proposed antenna for return loss, axial ratio, and total gain, are discussed in this section. It is observed from Figs 3 and 4 that the designs 1 and 2 show bad return loss performance with linear polarization. The return loss performance of design 3 improved a lot in the three impedance bandwidths because the input impedance is greatly changed after adding two opposite x-axis-directed rectangular

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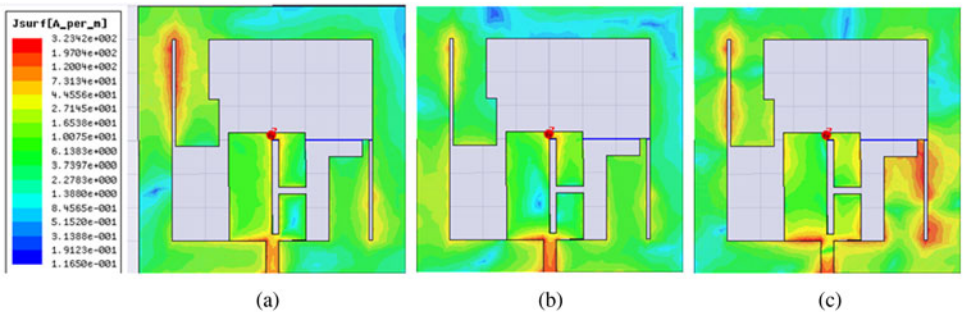

Fig. 6. Simulated surface current distributions of proposed antenna: (a) 2.65 GHz, (b) 4.45 GHz, and (c) 9.09 GHz.

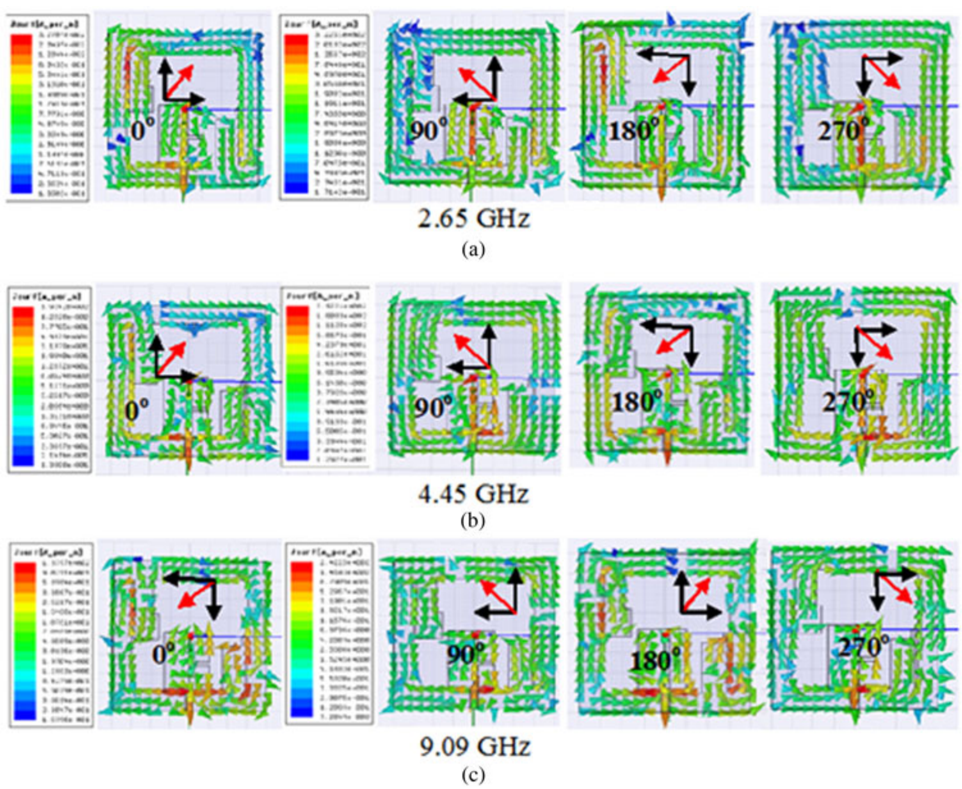

Fig. 7. Simulated magnetic current distributions for 0 and 90°: (a) at 2.65 GHz, (b) at 4.45 GHz, and (c) at 9.09 GHz.

strips, and the middle ARBW is achieved. However, the lower and upper ARBWs are still poor. A small rectangular strip added on the left-sided rectangular strip and a small rectangular slit cut on the right-sided rectangular strip can significantly develop the lower and middle ARBWs. Finally, the proposed design gives triple band with improved ARBW as right-hand circular polarization (RHCP) wave for lower and middle bands with left-hand circular polarization (LHCP) wave for the upper band of the impedance bandwidth. Figure 5 shows satisfactorily total gain for desired triple band of proposed antenna.

Surface current distribution

To study the generation of resonant modes, surface current distributions on the antenna at 2.65, 4.45, and 9.09 GHz are presented in Fig. 6. In Fig. 6(a), maximum currents are localized mainly in the upper left corner of the slotted ground and in bottom part of the patch to produce resonant modes at 2.65 GHz. At 4.45 GHz, the bottom part of the patch mainly contributes to the resonance from Fig. 6(b). In Fig. 6(c), the maximum current is distributed mainly along the lower right corner of the ground and in a small part of the patch to excite the resonant mode at 9.09 GHz.

Figure 7 shows the magnetic current distributions for different time phases of $\omega t = 0°$, $\omega t = 90°$, $\omega t = 180°$, and $\omega t = 270°$, at 2.65, 4.45, and 9.09 GHz, respectively. Two orthogonal resonant modes with a 90° phase difference and equal amplitude can realize CP radiation. It signifies the direction of the magnetic current vector at time phases $\omega t = 0°$ and 90°, which are equal in magnitude and opposite to time phases 180° and 270°, respectively. As shown in Figs 7(a) and 7(b), it can be observed that the combined effect of magnetic current vectors of a notched patch and ground plane gives CP wave rotation in the right-hand direction for the first and second bands, at 2.65 and 4.45 GHz, respectively; whereas

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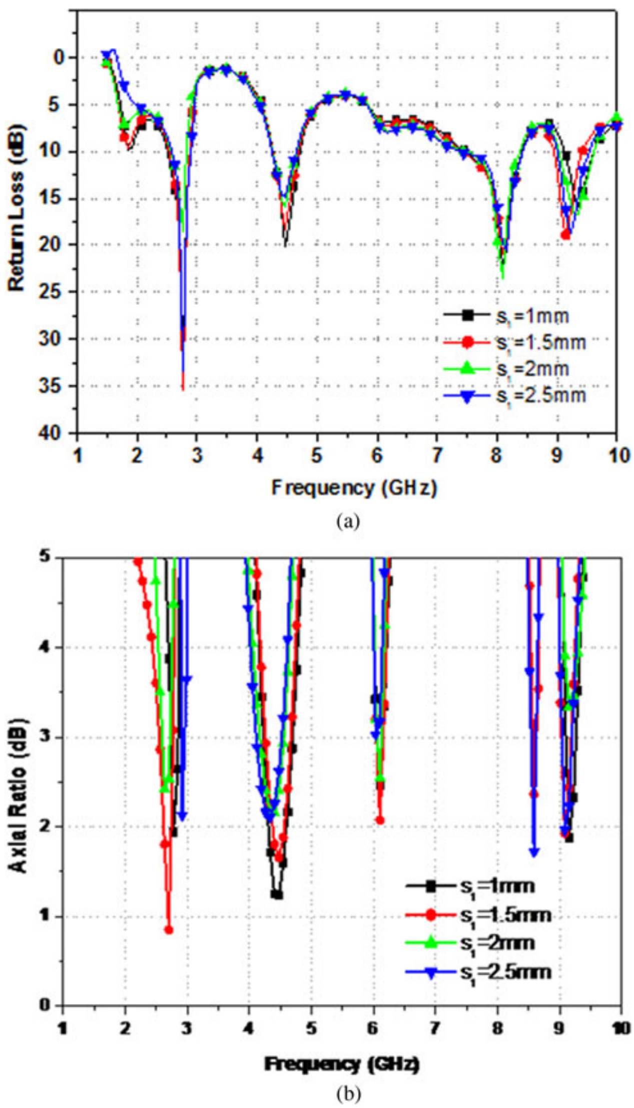


Fig. 8. Effects of varying s_1 on return loss and axial ratio.

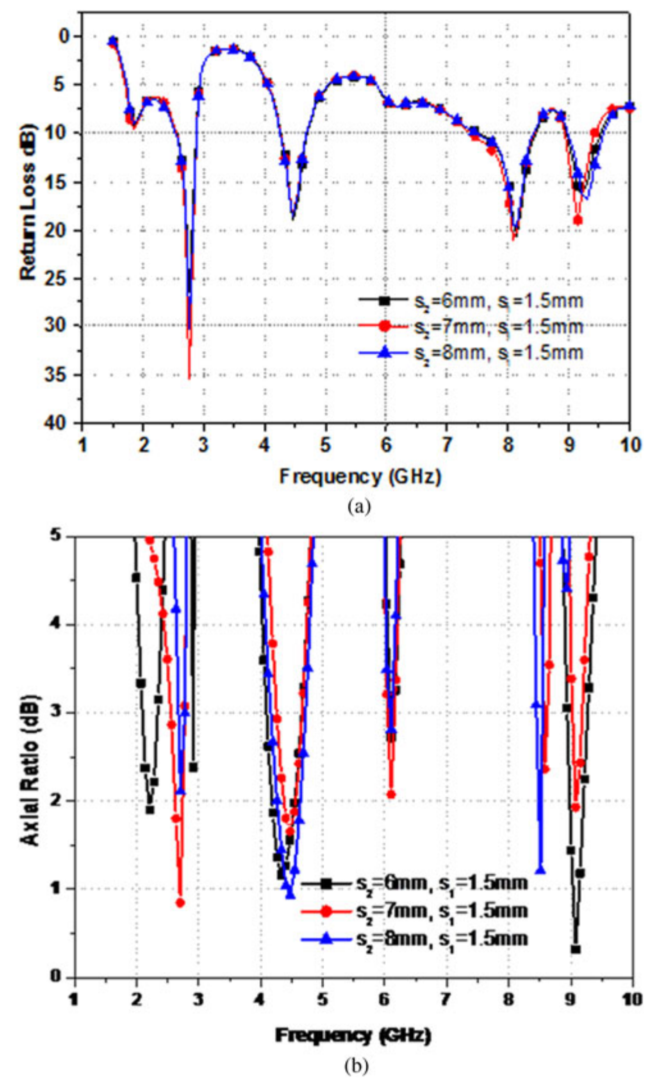


Fig. 9. Effects of varying s_2 on return loss and axial ratio.

the simulated magnetic current vectors of the proposed antenna in Fig. 7(c) give CP wave rotation in the left-hand direction for the third band, at 9.09 GHz.

Parametric analysis

In this section, a parametric analysis of the proposed antenna for further study was conducted. The results provide a useful guideline, to achieve desired operating bands with CP radiation. To know the effect of antenna parameters in the parametric analysis, at a time, only one parameter was varied, while other parameters were kept constant.

First studied parameters are the left rectangular small strip ($s_1 \times s_2$) at the lower ground. Figure 8 shows the influence on return loss and axial ratio with the increase of s_1. As shown in the figure, s_1 has no effect on return loss. However, the influence on the axial ratios is considerable. By varying s_1 from 1 to 1.5 mm, the first two ARBWs are significantly changed from 2.77–2.84 to 2.56–2.7 GHz and 4.19–4.68 to 4.12–4.54 GHz, respectively. The ARBW becomes poor with the further increase of s_1 from 2 to 2.5 mm. Figure 9 shows the influence on return loss and axial ratio with the increase of s_2. The variation of length s_2 has no effect on return loss. However, the influence on the axial ratio is drastic. The second ARBW becomes wider with the increase of s_2 from 6 to 8 mm.

Now, the second studied parameters are the right rectangular small slit ($s_3 \times s_4$) at the lower ground. The effects of the length s_3 on the impedance bandwidth and ARBW are presented in Fig. 10. As shown in Fig. 10, s_3 has influence on both return loss and axial ratio. When s_3 increases, the last impedance bandwidth is shifted toward the upper frequencies. In Fig. 11, the effects of s_4 on return loss and axial ratio for the proposed antenna are also investigated. It is found that s_3 and s_4 play an important role in circular polarization property of the antenna. As shown in Fig. 11, significant improvement of the axial ratio is observed by tuning s_4 and s_4.

Experimental results and discussion

This section explained the experimental results of the proposed antenna. Based on the optimized parameters, the antenna is

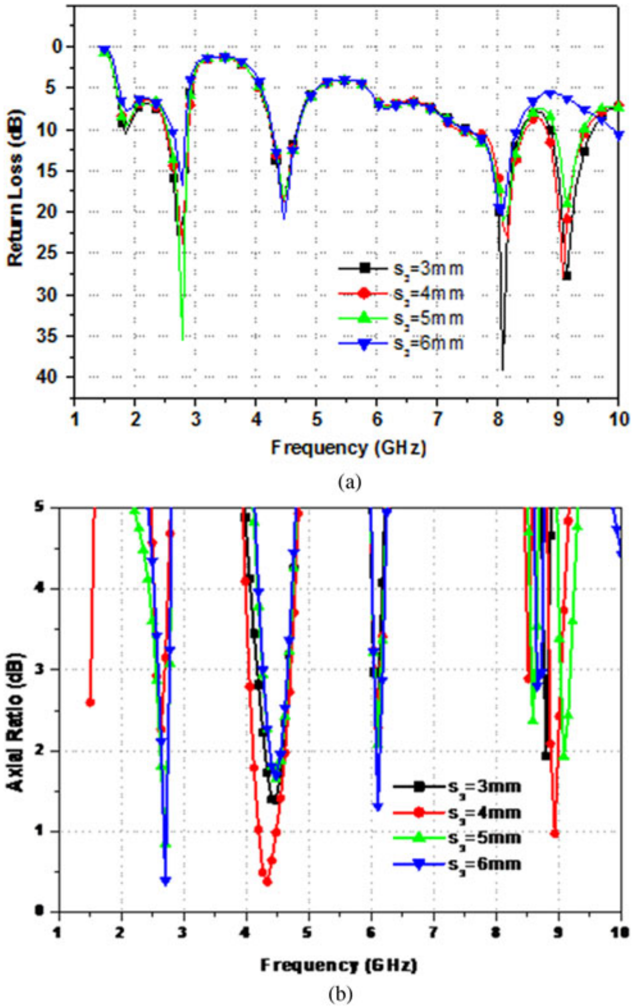


Fig. 10. Effects of varying s_3 on return loss and axial ratio.

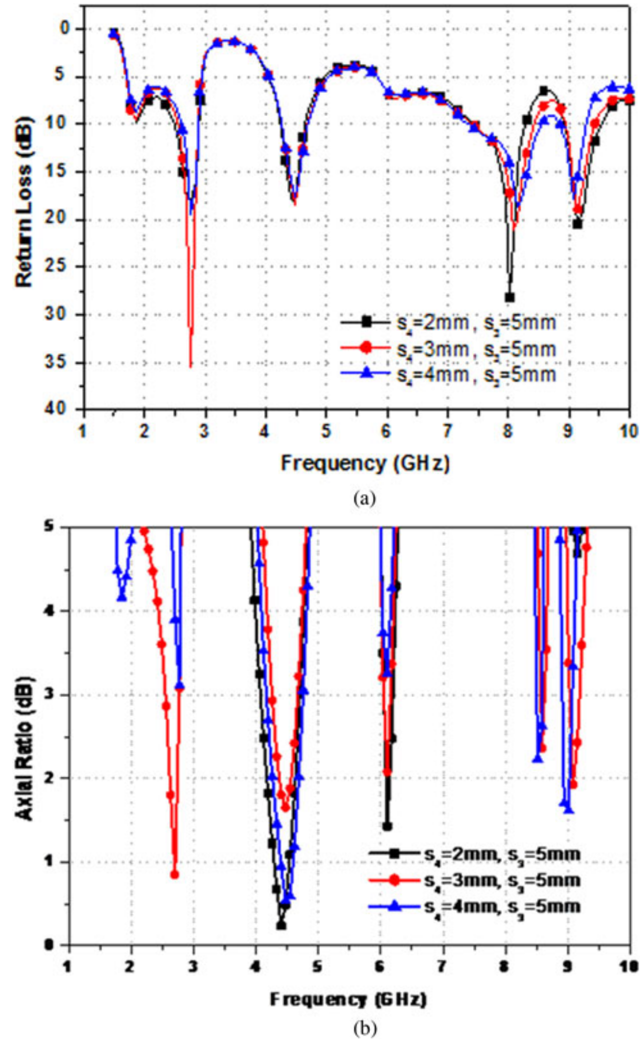
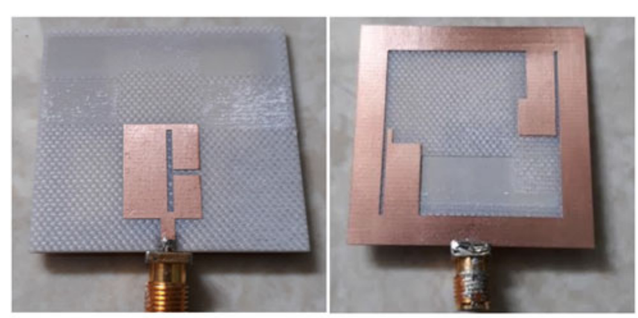


Fig. 11. Effects of varying s_4 on return loss and axial ratio.

fabricated and measured. The designed antenna has a total size of 40 mm × 40 mm × 1 mm that operates over triple impedance bandwidth of 340, 430, and 490 MHz. The 3 dB ARBWs are 200, 400, and 150 MHz, respectively, corresponding to the appropriate resonant frequencies over the three operating bands.

Fabricated antenna

The proposed antenna is fed using 50 Ω SMA connector placed along the microstrip feed line. The fabrication of proposed antenna is complete with optimized parameters, and measurement has been performed with the help of Agilent™ vector network analyzer of PNA-L series. The image of top and bottom views of the fabricated triple-band CP wide slot antenna prototype are shown in Figs 12(a) and 12(b).



(a) (b)

Fig. 12. Fabricated image of the proposed antenna: (a) top view and (b) bottom view.

Return loss and axial ratio

The results of the proposed triple-band CP wide slot antenna are discussed in this section. Figure 13 shows the variation of return loss with the frequency of the designed antenna. It is clear from the result that the antenna operates in a triple frequency band which is from 2.56 to 2.9 GHz for the first band, from 4.25 to 4.68 GHz for the second band, and from 8.93 to 9.42 GHz for the third band. Measured center frequencies have more than −10 dB return loss and are 2.73, 4.46, and 9.18 GHz for the first, second, and third bands, respectively. Due to the single-feed structure, a spurious resonant mode is generated at 8.18 GHz. This resonant mode is discarded, because of lack of gain and desired 3 dB ARBW. Furthermore, Fig. 14 shows the plots of measured and simulated ARBW against frequency. The measured result shows the 3 dB ARBW of about 200 MHz (2.55–

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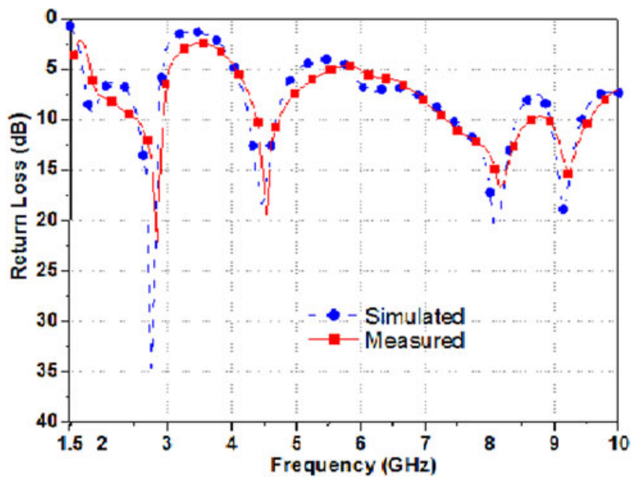

Fig. 13. Variation of return loss with frequency.

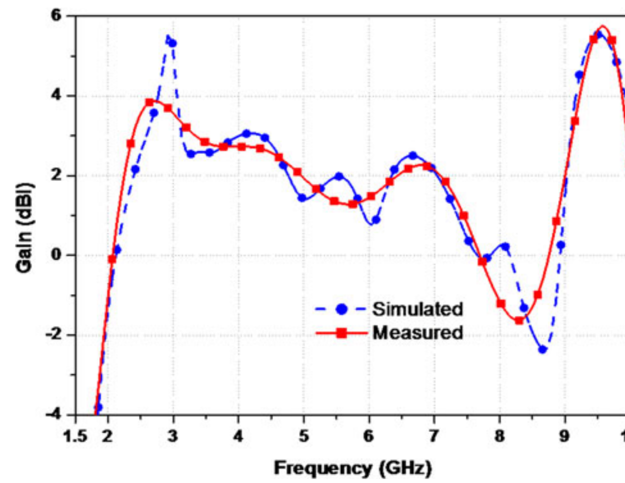

Fig. 15. Variation of gain with frequency.

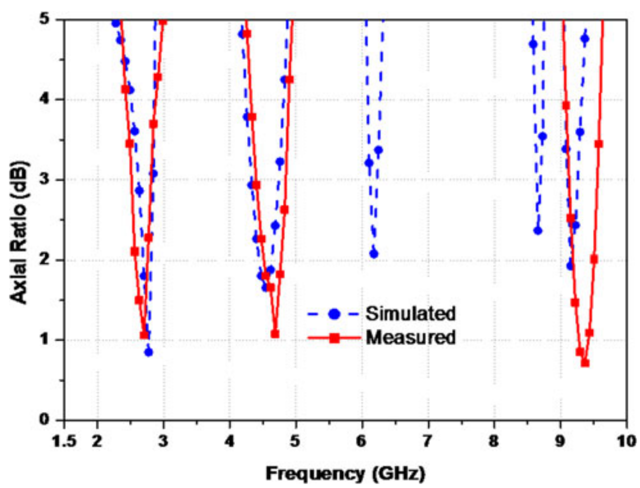

Fig. 14. Variation of axial ratio with frequency.

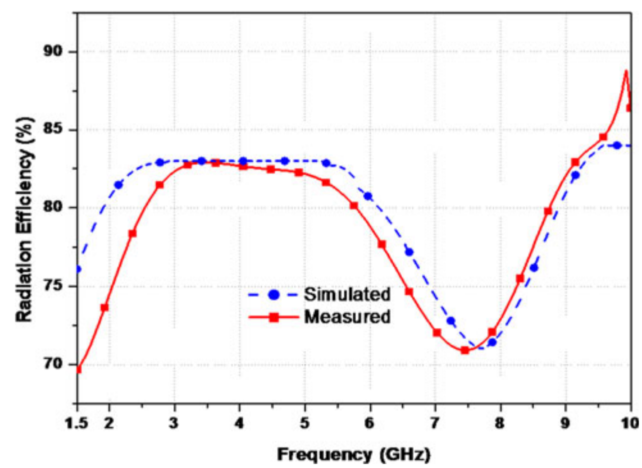

Fig. 16. Variation of radiation efficiency with frequency.

2.75 GHz), 400 MHz (4.25–4.65 GHz), and 150 MHz (9.02–9.17 GHz) at center frequencies of 2.65, 4.45, and 9.09 GHz, respectively. It seems that the simulated results agree reasonably well with the measured results.

Gain, radiation efficiency, and radiation pattern

Figure 15 shows an excellent agreement between the plots of measured and simulated total gain against frequency. It is observed that the antenna having highest peak gain of 3.03, 3.5, and 5.64 dBi at 2.65, 4.45, and 9.09 GHz center frequencies of CP band, respectively. Figure 16 gives the simulated and measured antenna efficiency performance of the triple-band CP antenna. The antenna efficiency is about 83% over the desired operating bands.

Radiation pattern of the proposed antenna in the *xz*- and *yz*-planes at 2.65, 4.45, and 9.09 GHz are shown in Figs 17(a)–17(c), respectively. The close observation of radiation pattern for desired operating triple frequencies illustrates that the RHCP wave is generated in the first two bands and LHCP wave in the third band. Almost boresight radiation patterns are observed at the lower and middle bands; however, the patterns at the upper band show a slight deviation from the broadside direction. This is mainly due to the effect of the currents on the lower right corner of the ground plane. The half-power beam-width (−3 dB) of the antenna in the *xz*- and *yz*-planes at 2.65 GHz are 57 and 75° (from −21 to 36° and from −34 to 41°°), at 4.45 GHz are 86 and 75° (from −46 to 40° and from −45 to 30°), and at 9.09 GHz are 17 and 52° (from −6 to 11° and from −48 to 4°).

To conclude the senses of the two CP waves, the left-hand and the right-hand components at all three frequencies are measured and are recorded in Fig. 17. At 2.65 and 4.45 GHz, the RHCP component is more than 20 dB higher than the LHCP component in the bore sight direction on the *xz*- and *yz*-planes. Otherwise, at 9.09 GHz, the LHCP component is more than 20 dB higher than the RHCP component in the bore sight direction on the *xz*- and *yz*-planes. As a result, the antenna radiates RHCP in the bore sight direction, at 2.65 and 4.45 GHz, and LHCP in the bore sight direction, at 9.09 GHz. The results of simulated radiation patterns are validated by comparing them with measured radiation patterns, to demonstrate the stability of radiation patterns at all three considered frequency. The simulated and measured results show good agreement between them. Minor differences

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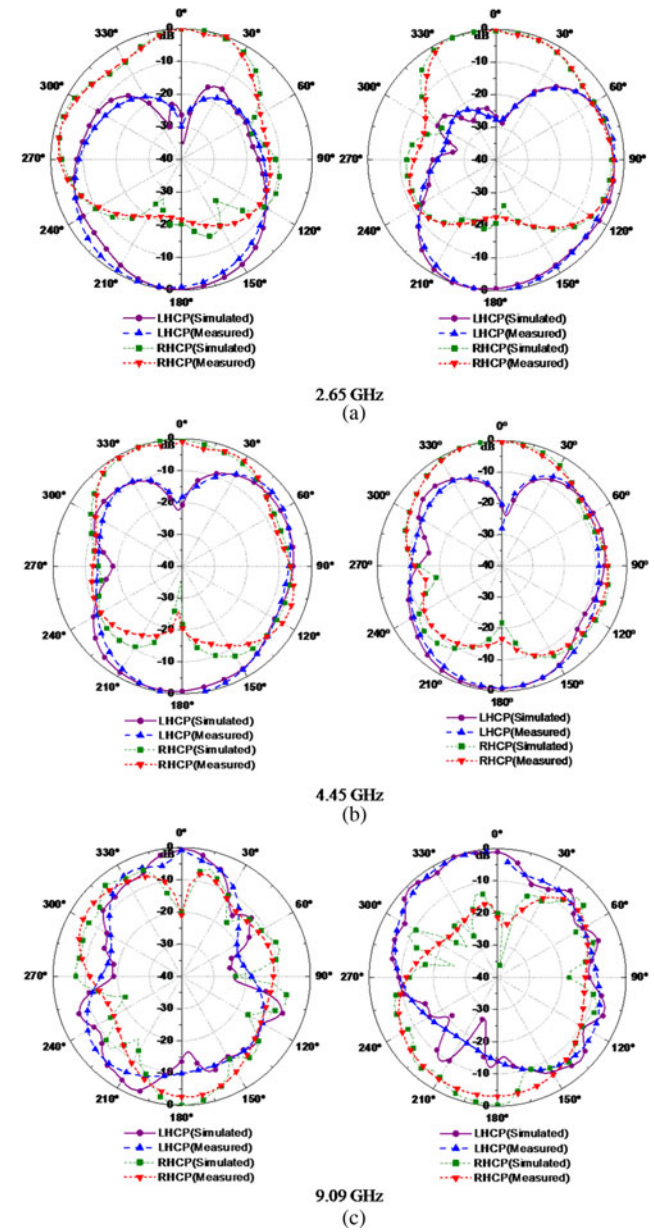

Fig. 17. Simulated and measured radiation pattern in the *xz*- and *yz*-planes: (a) at 2.65 GHz, (b) at 4.45 GHz, and (c) at 9.09 GHz.

Table 2. Comparison of triple-band circularly polarized antennas

Ref.	Antenna type	Antenna size (mm^3)	Impedance BW%	ARBW%
[27]	Annular slot	95 × 93 × 0.81	9, 2.5, 27	7.3, 1.3, 5.6
[28]	Stacking	80 × 80 × 4.724	1.7, 2, 2.5	3.4, 0.81, 0.83
[29]	Hexagonal slot	60 × 60 × 15	33.2, 22.7	1.7, 3.9, 5.2
[30]	Koch fractal	50 × 50 × 3.2	8.7, 2.4, 5	3.2, 1.6, 3
[31]	Stacking	40 × 40 × 4.57	4.4, 3.4, 7.2	0.4, 1.1, 0.7
Proposed	Wide slot	40 × 40 × 1	1.24, 9.63, 5.34	7.54, 8.98, 1.65

shown in the simulated and measured results are due to the fabrication imperfections and measurement errors.

Table 2 illustrates the comparison of proposed triple-band triple-sense CP antenna and the previous triple-band CP antennas. It shows that this antenna has a simpler structure, more compact size, and good impedance bandwidths with suitable ARBWs.

Conclusion

A microstrip-fed, rectangular patch loaded with *T*-shaped notch, wide slot antenna featured for triple-band CP has been designed and successfully implemented. The simulated antenna structure is quite capable in producing three frequency bands with desired 3 dB ARBWs. The measured gains are comparatively stable across all three CP bands. From the measured and simulated results, it is observed that the proposed antenna offers higher isolation between adjacent bands with good radiation pattern characteristics. The results obtained by simulation are acceptable with measured results. In addition with the feature of a simple and compact topology, the antenna is low-cost and is suitable for multi-band wireless communication.

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