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RESEARCH ARTICLE

A Compact Triple-Band and Dual-Sense Circularly Polarized Truncated Patch Antenna

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ABSTRACT A triple-band dual-sense circularly polarized truncated patch antenna is proposed. The truncated patch is fed by the aperture etched on the ground plane. Firstly, a *y*-axis directional rectangular slot is introduced in the truncated patch to excite two orthogonal modes for left hand circular polarization(LHCP). Then an *x*-axis directional rectangular slot is employed to obtain right hand circular polarization (RHCP) performance. After that, one parasitic stub is loaded in the central of the *x*-axis directional rectangular slot, thus, an extra RHCP can be realized. Finally, the other parasitic stub is loaded beneath the truncated patch to improve the impedance and axial ratio performances. The etched slots and loaded stubs technologies are used in a single radiating patch to realize different senses at three different operating bands. And the senses and operating bands can be controlled by tuning according slots and stubs. Consequently, a compact triple-band dual-sense circularly polarized antenna is successfully designed. The 3-dB axial-ratio bandwidths of the proposed antenna are 2.6% (3.55-3.64 GHz), 0.24% (4.175-4.185 GHz), and 0.47% (4.26-4.28 GHz), respectively.

INDEX TERMS Triple-band, circularly polarized, patch antenna, stub, slot.

I. INTRODUCTION

Circularly-polarized antennas have been widely studied for their advantages of eliminating multipath interference and signal weakening, reducing the energy decay caused by Faraday rotation effect in the ionosphere, and having no polarization adaptation loss. Due to the scarcity of spectrum resources, a single antenna is required to work in multiple frequency bands. So the multi-frequency circular polarization antenna becomes the focus of research. Therein multi-frequency circularly polarized antennas with different senses (left or right hand circular polarization) (RHCP or LHCP) in different frequency bands are favored as they can play an important role in satellite navigation system.

The realization of multi-frequency circularly polarized antenna can be summarized into three methods: using multi patches [1], [2], [3], [4], [5], [6], [7], [8], etching slots on a single patch or using slot antenna [9], [10], [11], [12], [13], [14] and loading stubs on a single patch [15], [16], [17]. In [1], two stacked patches etched unsymmetrical U-slot were used to achieve dual-band and dual-sense circularly polarized performance. In [2], three stacked cornered patches worked at different frequencies are used to achieve right-hand circularly polarized functions in three frequency bands of Global Positioning System (GPS). In [3], [4], [5], and [6], the same stacked patch in the vertical direction technology was used to realize multi-band dual-sense circularly polarized performance. In addition to the method of stacking patches in the vertical direction, multiple radiation patches can also be used in the horizontal direction to achieve dual-band dual-sense circularly polarized characteristics [7], [8]. The multi patches method mentioned above has the advantage of easy to realize multi-band dual-sense circularly polarized performance. However, they are too bulky for portable terminals and suffering high cost compared to a single patch. In order to reduce the size and cost of the antenna, etching slots in

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a single patch, using slot antenna and loading stubs at a single patch technology are appeared. In [9], an S-shaped slot was etched in the center of the patch and fed by slits coupling to realize dual-band circular-polarized performance. However, the dual-band both exhibited LHCP performance. In [10], a cross slot etched in the center of the circular radiation patch and an open annular slot etched along the circumference to obtain dual-band and dual-sense circular polarization characteristic. However, the frequency ratio was big. In [11], an asymmetric U-shaped slot and an inverted L-shaped slot were etched in the ground to realize dual-band dual-sense circular polarization performance. And the antenna also suffered big frequency ratio. In [12], a L-shaped radiators were used to generate three resonant frequencies, and two rectangular strips with different sizes were added at the corners of the ground to produce triple-wide band triple-sense circular polarization waves. However, the radiation patterns of the triple-band were not similar. In [13] and [14], slots etched technology were used to realize triple-band circularly polarized antenna. However, the triple-band all exhibited RHCP performance. In [15], [16], and [17], the loading stubs technology was applied. The dual-band circular polarization characteristics can be realized. However, the frequency ratio cannot be flexibly controlled. Combine the etching slot and loading stubs technologies, a triple-band antenna with different senses of circular polarization was presented [18]. In general, there are few studies about triple-band dual-sense circularly polarized antenna using a single radiating patch studied.

In this paper, a compact triple-band dual-sense circularly polarized antenna is proposed. It employs etching slot and loading stubs technology, unlike [18], the stub is loaded in the inner of the patch, which is facilitated to further miniaturization. Firstly, a *y*-axis directional rectangular slot and a stub loaded in the central of the *y*-axis directional slot are employed to realize RHCP. Then an *x*-axis directional rectangular slot is introduced to generate LHCP. After that, an additional stub loaded beneath the patch is designed to improve the impedance bandwidth and the circularly polarized performance. Finally, the antenna can operate at 3.6 GHz for LHCP, 4.2 GHz for LHCP and 4.3 GHz for RHCP.

II. ANTENNA STRUCTURE AND WORKING PRINCIPLE

A. ANTENNA CONFIGURATION

The figuration of the proposed triple-band dual-sense circularly polarized patch antenna is shown in Fig.1. As can be seen from Fig.1, the antenna consists of two layers of dielectric substrate with relative dielectric constant 2.55, tangent of loss angle 0.0029 and thickness 0.8 mm. An air gap of 4.2 mm is existed between the two substrates. And the two dielectric substrates are secured by numbers of nylon columns. The radiating patch is printed on the top surface of the upper substrate. The ground plane with an inclined rectangular aperture and a microstrip feeding line along the diagonal direction are printed on both sides of the lower substrate.

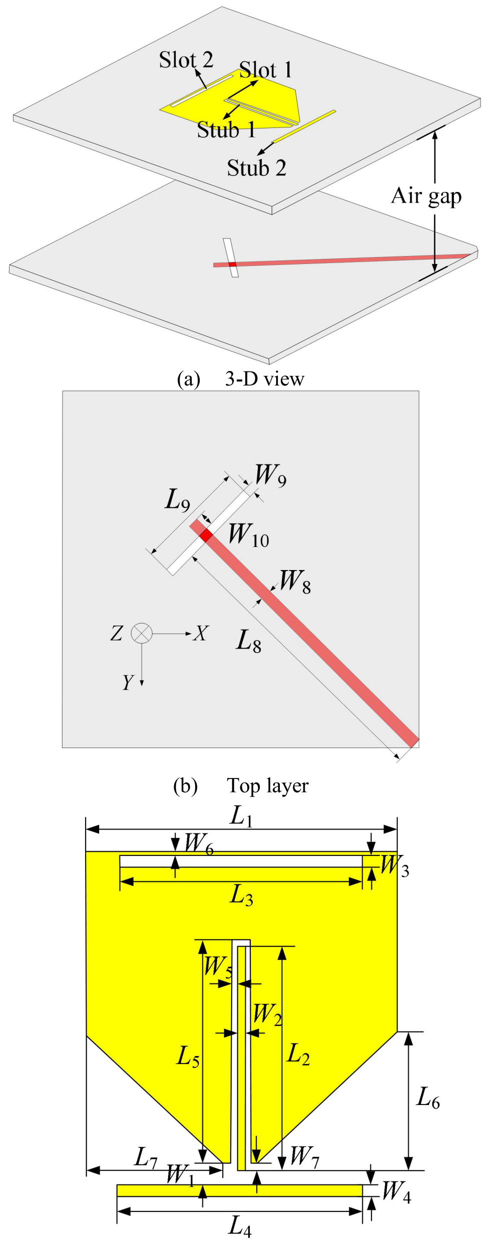

FIGURE 1. Configuration of the proposed triple-band dual-sense CP patch antenna. (a) 3-D view. (b)Top layer. (c) Bottom layer L_1 = 35 mm, L_2 = 27.1 mm, L_3 = 25.7 mm, L_4 = 27.2 mm, L_5 = 25 mm, L_6 = 15.5 mm, L_7 = 14.2 mm, L_8 = 74.5 mm, L_9 = 25 mm, W_1 = 2.2 mm, W_2 = W_3 = 1.1 mm, W_4 = 1.8 mm, W_5 = W_8 = 2.2 mm, W_6 = 0.5 mm, W_7 = 0.5 mm, W_9 = 1.8 mm, W_{10} = 3.8 mm.

And the ground plane with an inclined rectangular aperture is printed on the top side of the lower substrate, the feeding line is printed on the back side. The rectangular radiating patch is triangular corner cut at the inferior two rig- ht angles. A *y*-axis directional rectangular slot named Slot 1 is etched at the lower margin of the patch. An *x*-axis directional rectangular slot named Slot 2 is etched at the upper margin of the patch. And Moreover, a *y*-axis directional rectangular stub named Stub 1 is loaded at the central of Slot 1, and an *x*-axis directional

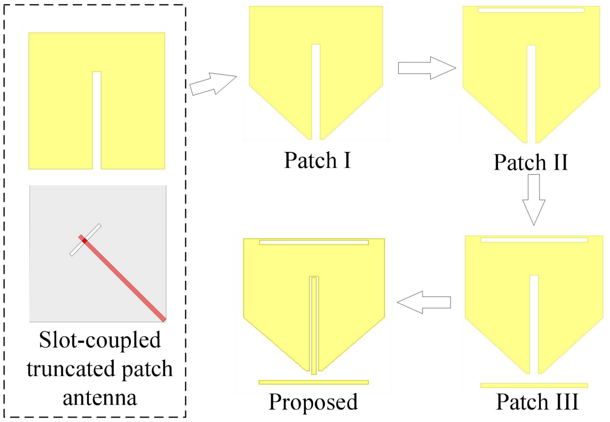

FIGURE 2. Evolution of the proposed antenna.

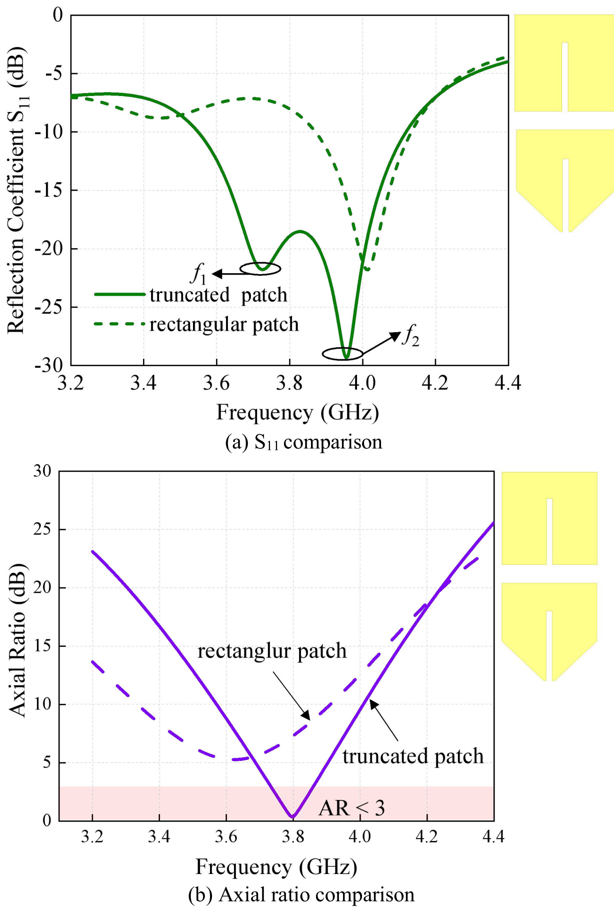

FIGURE 3. S_{11} **and axial ratios of the slot-coupled truncated patch and rectangular patch antenna.**

rectangular stub named Stub 2 is loaded beneath the patch. The proposed antenna is fed by the microstrip feeding line coupled to the radiating patch through the ground plane aperture. By etching the two slots and loading the two stubs, the triple-band and dual-sense circularly polarized antenna using a single patch can be realized. The detail operating principle is elaborated in the following part.

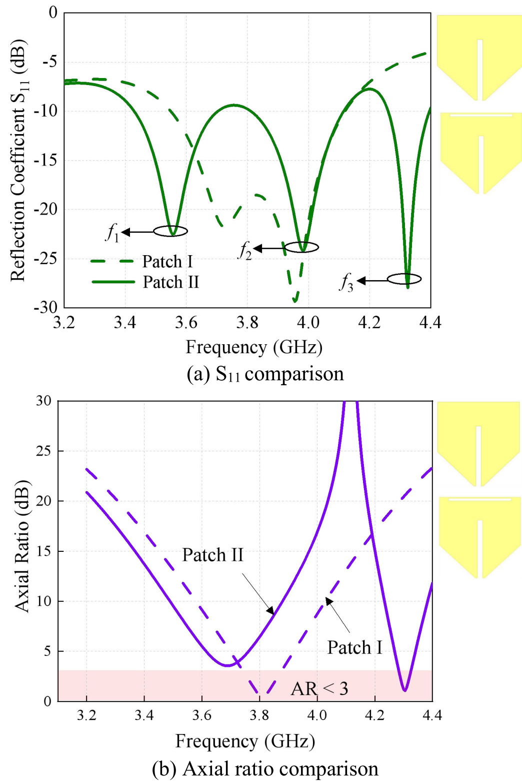

FIGURE 4. S_{11} **and axial ratios of the slot-coupled truncated patch antenna with Patch I and Patch II.**

B. WORKING PRINCIPLE

To illustrate the working principle of the proposed antenna. The evolution of the proposed antenna is depicted in Fig.2. The proposed antenna originates from a traditional aperture-coupled patch antenna. The patch radiator here is selected to be a rectangular one with a y-axis directional rectangular slot etched at the lower margin of the patch (Slot 1). By etching a slot in the patch, two resonating modes can be introduced [19]. As seen from Fig. 3, the two resonating modes are named f_1 and f_2, respectively. And f_1 is employed by the Slot 1, while f_2 is employed by the patch itself. Based on a truncated patch structure, the current path on the patch is lengthened, the resonator mode of the patch should be shifted to the lower band. Hence, the conclusion of f_2 is generated by the patch itself is drawn. As f_1 is introduced by the Slot 1, it is a circularly-polarized mode, while f_2 is a linearly-polarized one. The principle of f_1 is a circularly-polarized mode is analyzed in the following part. Firstly, the rectangular patch is truncated, Patch I is realized. Compared to the original patch, Patch I has the better performances of impedance matching and axial ratio. Secondly, an x-axis directional rectangular slot (Slot 2) is etched at the upper margin of Patch I to obtain Patch II. It can be seen from Fig. 4 that, an extra resonating mode (f_3) is achieved and is also a circularly-polarized one. Thirdly, an x-axis directional rectangular stub (Stub 2) is loaded beneath Patch II, Patch III is realized. As seen from Fig. 5, there are a new added resonating mode (f_4) in Patch III.

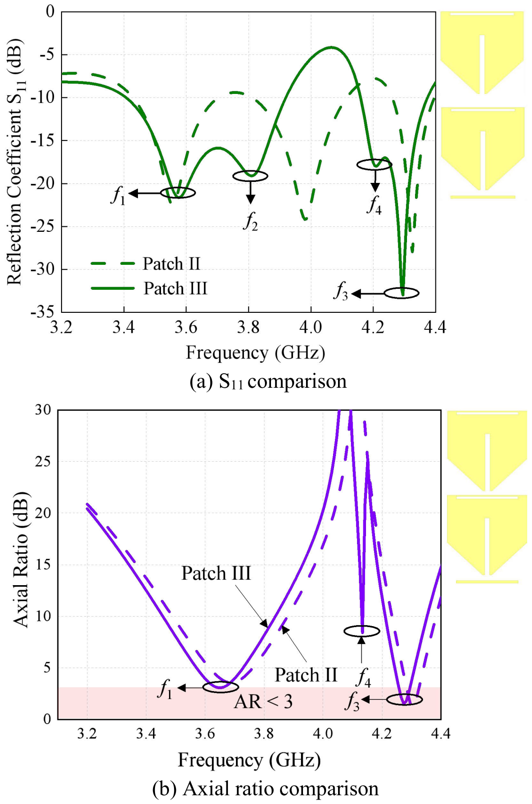

FIGURE 5. S_{11} **and axial ratios of the slot-coupled truncated patch antenna with Patch II and Patch III.**

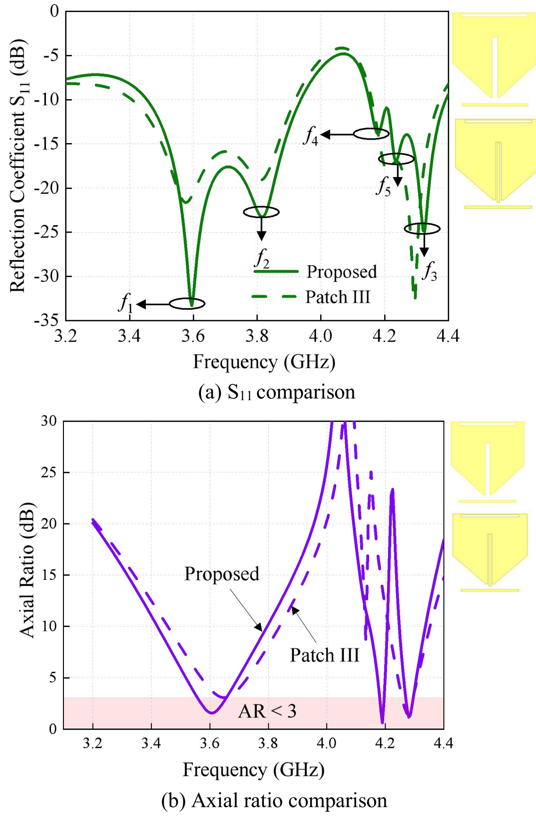

FIGURE 6. S_{11} **and axial ratios of the slot-coupled truncated patch antenna with Patch III and the proposed one.**

And the mode f_4 is also a circularly-polarized mode, the axial ratio of this mode is about 8.5 dB. However, this mode is hard to control. Then it is used as a linear-polarized one to widen the impedance bandwidth. Finally, based on Patch III, a y-axis directional rectangular stub (Stub 1) is loaded at the central of Slot 1, the proposed antenna is achieved. The proposed antenna has five resonating modes (f_1,f_2,f_3,f_4,f_5), and f_5 is introduced by the Stub 1. Moreover, f_5 is also a circularly-polarized mode, which can be seen from Fig. 6. Therefore, there are three circularly-polarized modes in the proposed antenna. In summary, f_1 is employed by the Slot 1, f_2 is employed by the patch itself, f_3 is employed by the Slot 2, f_4 is employed by the Stub 2 and f_5 is employed by the Stub 1. It is worth mentioning that the f_1, f_3 and f_5 are the three circularly-polarized modes in the proposed antenna.

The detailed generation mechanisms of the circularly-polarized modes are analyzed as below. As seen in Fig. 7 (a), when Slot 1 is excited in the diagonal direction of the patch, the current path lengths of the two vertical components of J are different. And Jy flows ahead of Jx, then Jrotates clockwise, which is known as LHCP. And when Slot 2 is excited in the same direction, as shown in Fig. 7 (b), at this time, Jx flows ahead of Jy, then Jrotates counter-clockwise, which is known as RHCP. While Stub 2 is introduced in Slot 1, as seen in Fig. 7 (c), the signal coupled from Slot 1 to Stub 1 will be out of phase, thus the direction of the excitation is opposite to Fig. 7 (a) and Fig. 7 (b), and at this moment, Jx still flows ahead of Jy to realize RHCP, although Slot 1 and Stub 1 are in parallel.

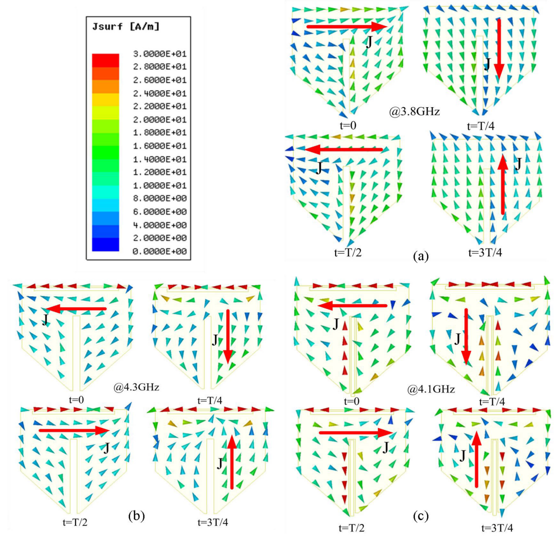

FIGURE 7. Current distributions on the (a) Patch I at 3.8 GHz, (b) Patch II at 4.3 GHz, (c) Proposed one at 4.1 GHz.

The vector current distributions orientated at t = 0, T/4, T/2 and 3T/4 of the three circularly-polarized modes are shown in Fig. 8, respectively. It can be seen that the main current

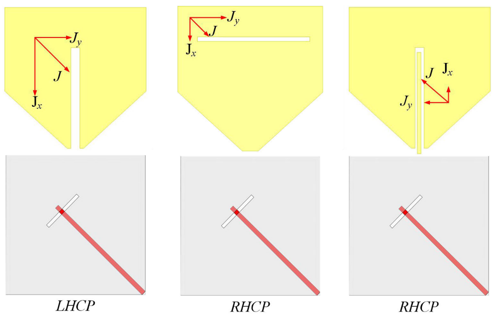

FIGURE 8. Diagrammatic drawing of the mechanism of the circular polarization.

J of the first circularly-polarized mode at 3.8 GHz rotates clockwise, and shows *LHCP* characteristic. The main current *J* of the second circularly-polarized mode at 4.3 GHz rotates counter-clockwise, which is seen as *RHCP*. And the third one *at* 4.1 GHz shows the same performance as the second one.

C. PARAMETERS ANALYSIS

In this part, the influences of the key parameters of the triple-band and dual-sense circularly polarized antenna on the axial ratio are analyzed. On the conditions of the dielectric substrate, the air layer and the feeding structure keeping unchanged, the axial ratio of the antenna is mainly affected by the size of the truncated patch (L_1), the lengths of Slot 2 (L_3) and Stub 1 (L_2). For this antenna, the three circularly-polarized modes can be adjusted independently. That is, for example, when L_1 is adjusted, the first circularly-polarized mode is changed while the other two modes basically remain unchanged.

As shown in Fig. 9, the other dimensions of the antenna remain unchanged. When L_1 is increased, the first circularly-polarized mode at 3.6 GHz moves to the low frequency, while the second and the third one is basically unchanged, as shown in Fig. 9 (a). When L_3 are increased, the first circularly-polarized mode is almost unchanged, the second circularly-polarized mode moves to the low frequency, and the third band moves slightly towards the high frequency, as shown in Fig. 9 (b). In Fig. 9 (c), when L_2 are increased, the first and the third circularly-polarized modes are also almost unchanged and the second circularly-polarized mode moves to the low frequency.

III. ANTENNA IMPLEMENTATION

As verification, a triple-band dual-sense circularly polarized truncated patch antenna based on slots and stubs loading is fabricated and tested in this section. The fabrication prototype and the measured results are depicted in Fig.10. The fabricated antenna is designed to operate at 3.6 GHz with LHCP, 4.19 GHz with RHCP, and 4.28 GHz with RHCP, which is regarded as an example to verify the design method. And the three CP bands can be controlled to the desired frequencies by optimizing the lengths of the Slot 1, Slot 2 and

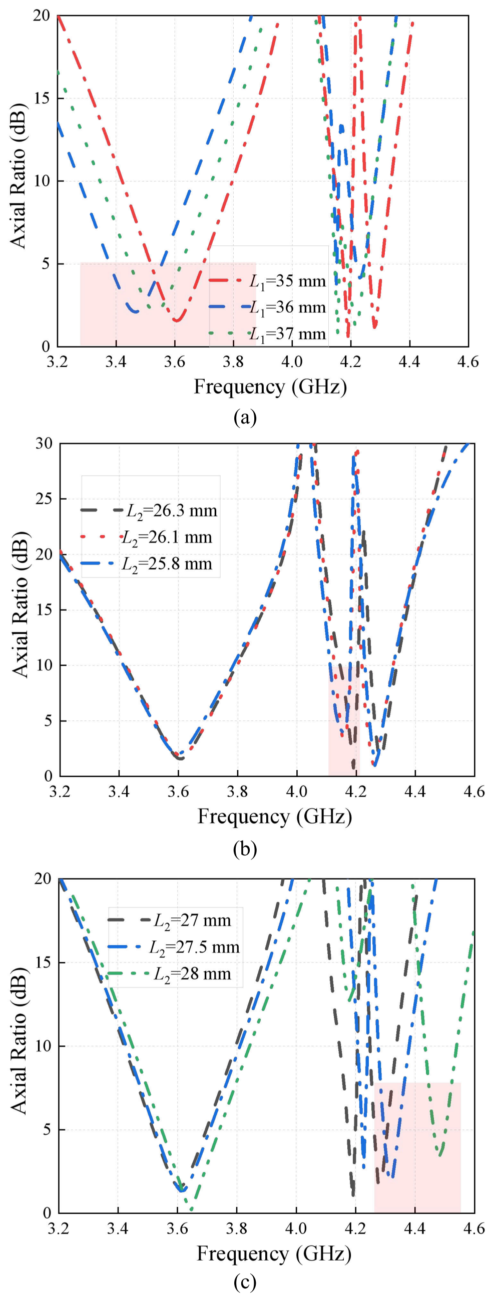

FIGURE 9. Axial ratio of the proposed antenna against the parameters (a) L_1, (b) L_3 and (c) L_2.

Stub 1. All the measured results were obtained by Agilent 5071C network analyzer and Satimo Starlab system. The measured impedance bandwidth is 12.2 % (3.44-3.88 GHz), 5 % (3.44-3.88 GHz). And the measured 3-dB AR bandwidths at the triple- band are 2.6 % (3.55-3.64 GHz), 0.24 % (4.175-4.185 GHz), 0.47 % (4.26-4.28 GHz), respectively. The measured average gains of the triple-band are 9.46, 4.7 and 7.4 dBic. It is worth mentioning that, as the signal coupled from Slot 1 to Stub 1 will be out of phase, the current direction on the Stub 1 is opposite to that of the truncated patch, resulting in current cancellation. Hence, the gain at 4.9 GHz is lower than that of 3.6 GHz.

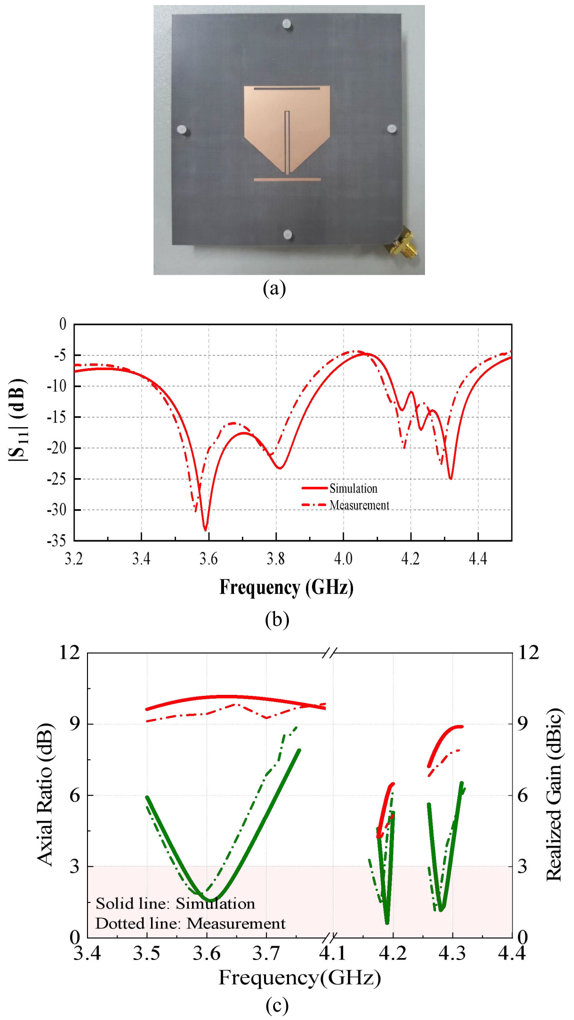

FIGURE 10. Results of the proposed antenna including (a) antenna prototype, (b) reflection coefficient S_{11} and (c) gain and AR.

To address the advantages of the proposed antenna, the performance comparison is tabulated in Table 1. In [2], stacked three patches were designed to realize triple-band circularly-polarized function and in [4] and [5], stacked two patches were employed to realize dual-CP operation. Since the antennas mention above used independent patch radiators, it was possible to control the frequency ratio of the circularly-polarized bands. Moreover, the structures of the three antennas were complex. In [9], [15], and [16], the antennas realized dual-band dual-sense circularly-polarized performance, however, the bandwidths were limited or cannot be controlled. In [12], a triple-band and triple-sense circularly-polarized antenna was proposed, but the circularly-polarized frequencies cannot be controlled and the gains were low. In summary, compared to the above antennas, the proposed work realizes a very compact structure with a single radiating patch and the triple-band dual-sense circularly-polarized operation. Moreover, the frequencies of the three circularly-polarized frequencies can be controlled and optimized.

TABLE 1. Performance comparison.

Ref.	Realization	AR (bandwidth /bands)	Polar.	Gain (dBi)	Size (mm^3)
[2]	Triple-layer stacked patches	3.4%/ 0.81%/2% /Triple	Single	5.6 /5.6 /6.3	80*80 *4.724
[4]	Dual-layer stacked patches	1.07% /1.19% /Dual	Dual	4.5 /4.5	100*100 *8.6
[5]	Dual-layer stacked patches	1%/1% /Dual	Dual	3.3/4. 2	70*70 *4.8
[9]	Slotted patch	6.9%/0.6% /Dual	Single	5.0 /5.0	115*115 *21.52
[12]	Slot antenna	35.9% 44%/6.3% /Triple	Dual	4.2 /3.7 /3.5	60*60*1
[15]	Stubs loaded antenna array	0.67%/0.6% /Dual	Dual	10.8 /12.5	140*150 *3.18
[16]	Stubs loaded antenna	0.3%/0.7% /Dual	Dual	7.5 /7.5	110*110 *3
This work	**Stubs and slots loaded antenna**	**2.6%/0.24 %/0.47% /Triple**	**Dual**	**9.46 /4.7 /7.4**	**85*85 *5.8**

IV. CONCLUSION

A compact triple-band dual-sense circularly polarized antenna using a single radiating patch is presented. The triple-band and dual-sense circularly polarized operation is realized by etching two slots and loading a stub at the patch. The detailed operating mechanism is elaborated in the paper. And the antenna is fabricated and tested. The measured results show the antenna can operate LHCP at 3.6 GHz, RHCP at 4.19 GHz and 4.28 GHz as predicted. The consistency of the simulated and measured results also shows the accuracy of the design method.

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