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Broadband Circularly Polarized Antenna With Non-Planar Reflector

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ABSTRACT In this article, a compact broadband circularly polarized (CP) antenna with non-planar reflector is presented. In this antenna, two fan-shaped cross-dipoles as the primary radiator and a stepped ground as a reflector are proposed to generate a broadband CP radiation. Besides, four L-shaped patches are introduced to effectively extend the bandwidth (BW) and extract a gain improvement together with the stepped ground. The measured -10 dB impedance BW is 132.08 % (1.36-6.65 GHz) and 3 dB axial ratio (AR) BW is 128.6% (1.39-6.4 GHz), closely with the simulated AR BW 136.73% (1.18-6.28 GHz), showing the proposed antenna features a wider bandwidth, comparing with other broadband CP antennas using similar structures. Due to the compact structure, the overall size of the proposed antenna is only $0.27\lambda_l \times 0.27\lambda_l \times 0.12\lambda_l$ (where λ_l is the free-space wavelength at 1.36 GHz). The proposed antenna has a wide application scope, such as the wireless network and satellite telecommunications.

INDEX TERMS Circularly polarized, stepped ground, cross-dipoles, wideband antenna.

I. INTRODUCTION

Circularly polarized antenna has been widespread used in current wireless communication, such as Navigation Positioning System, and Wireless Local Area Networks(WLAN). Currently, China employs the bands of 3.3-3.6 GHz and 4.8-5.0 GHz for sub-6-GHz 5th generation (5G) new radio (NR). The broadband CP antenna with low cost is desired to meet the tremendous requirement of 5G mobile networks. Thus, low-profile and low-cost with widely overlapping bandwidth CP antennas deserve further research and discussion.

As a main approach to realize CP, recently, the cross-dipole antennas have drawn much attention and interest in academia. For cross-dipole antennas, CP characteristics are mainly produced by two feeding excitations with equal magnitude and 90° phase difference. In the recently, many different CP antennas with cross-dipole structures have been proposed in [1]–[6]. In [1], the antenna uses two classical orthogonal straight dipoles and four coupled rotated metallic plates to realize wideband CP radiation. In [2], two crossed trident-shaped dipoles are employed to achieve a broadband characteristic in three bands. In [3], the crossed bowtie dipoles are introduced to broaden axial ratio (AR) BW. With parasitic modified patches in [4], the antenna obtains a -10 dB impedance bandwidth (BW) of 99.2% and AR BW of 72.7%. A broadband CP cross-dipole antenna using a circular ring reflector with improved AR and gain performance was presented in [5]. To achieve low profile and broadband AR bandwidth, an AMC structure is utilized in [6].

In general, the feeding methods of the CP antenna have two categories: single-feed and multi-feed. For multi-feeding, additional phase shifter [7] or complex power divider [8] are required, significantly increasing the complexity of the antenna. On the contrary, single-feed has a distinct advantage in simple structure [9], [10]. To achieve broadband, many other derived feeding structures have been proposed, such as the single L-shaped probe [11], the Z-shaped coupling feedline [12], and the coplanar waveguide (CPW) [13].

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Parasitic patches are generally used to achieve a broader bandwidth. In [11], four parasitic elements are employed to achieve the AR BW of 28.6%. In [14], two U-shaped parasitic patches are utilized to obtain wideband operating frequency. In [16], by adopting four sequentially rotated parasitic strips, the AR BW of the antenna is increased to 11.55%.

To achieve broadband CP, a fan-shaped cross-dipole antenna with non-planar reflector is proposed in this article. By the employed of the stepped ground, the bandwidths are significantly improved. Moreover, the bandwidth is further enhanced by L-shaped parasitic patches, four Z-shaped plates and four metal posts. The structure is compact with an overall dimension of $0.27\lambda_l \times 0.27\lambda_l \times 0.12\lambda_l$. The measured impedance BW for $|S_{11}| \leq -10$ dB is 132.08 % (1.36-6.65 GHz), and AR BW for $AR \leq 3$ dB is 128.6 % (1.39-6.4 GHz). The antenna has been simulated in ANSYS High Frequency Structure Simulator (HFSS). The proposed antenna has a prominent performance in impedance BW and AR BW, in comparison of other designs using the similar configuration.

This article is organized as follows. Section II describes the configuration and the design strategy of the antenna, and the major parameters analysis. Section III provides the measured results of the proposed antenna with comparison between other cross-dipoles designs. Conclusions are presented in section IV.

II. ANTENNA CONFIGURATION AND DESIGN STRATEGY

A. ANTENNA CONFIGURATION

Fig.1 shows the geometry of the proposed antenna, which consists of a stepped ground, two fan-shaped cross-dipoles, four Z-shaped plates, four L-shaped parasitic patches, and four metal posts. The main radiator is printed on both sides of a substrate with a dielectric constant of 4.1, a loss tangent of 0.003 and a thickness of $h_1 = 1.6$ mm. The cross-dipoles are centrosymmetric and etched on both sides of the substrate plate, and each pair is composed of two same cross-dipoles arms with arch height r_3 and chord length w_3. They are fed by a $50-\Omega$ coaxial cable. The outer conductor of the coaxial probe is connected to the dipoles printed on the bottom layer and the stepped ground, which is shown in Fig.1(b) and (c). The four copper plates are used to enhance the bandwidth of circularly polarized cross-dipole antenna. They are placed around the stepped ground. The cross-dipoles are surrounded by the parasitic patches. As shown in Fig.1(a), r_2 is the center distance between the parasitic patches and the cross-dipoles. The metal posts are connected to the top or the bottom layer of the cross-dipoles, respectively. Both of them have the same diameter. In Fig.1(c), the stepped ground consists of three layers. The height of each layer is 1 mm, and the widths of them are l_5, l_6, and W at the top, middle, bottom layer, respectively. As shown in Fig.1(c), the top and middle layers are copper rings. The bottom layer is a copper ground with four Z-shaped copper plates. Three layers are bonded by metal paste. It is used as a reflector to obtain unidirectional radiation patterns.

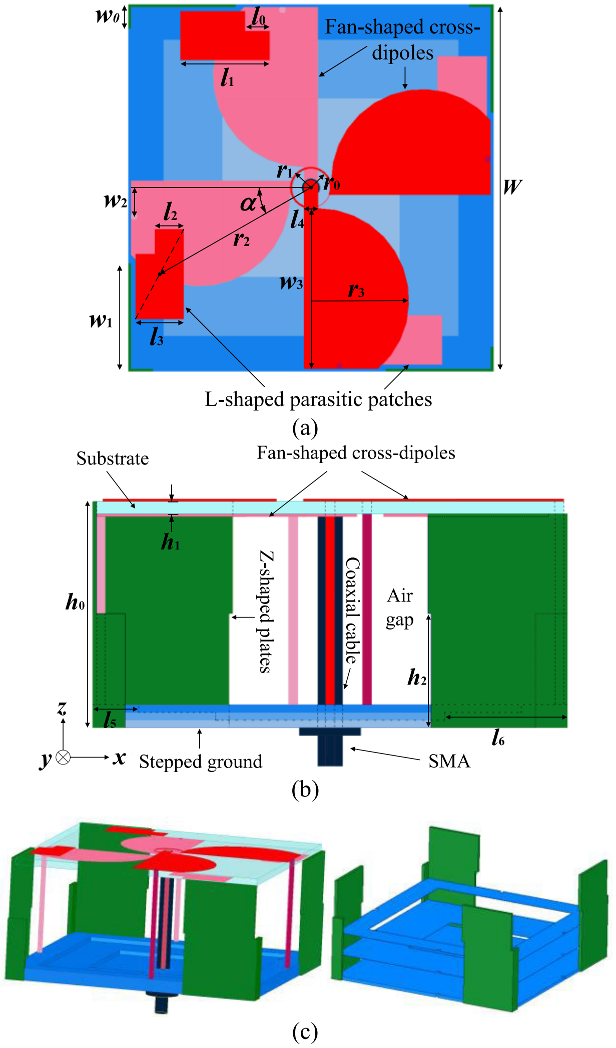


FIGURE 1. Configuration of the proposed cross-dipole antenna. (a) Top view. (b) Side view. (c) Perspective view and configuration of the non-planar reflector. $W = 60.8$ mm, $w_0 = 3.4$ mm, $w_1 = 17$ mm, $w_2 = 4.9$ mm, $w_3 = 27.4$ mm, $l_0 = 4.9$ mm, $l_1 = 15.83$ mm, $l_2 = 4.88$ mm, $l_3 = 7.74$ mm, $l_4 = 2.37$ mm, $l_5 = 7.46$ mm, $l_6 = 16.4$ mm, $\alpha = 29.59°$, $r_0 = 2.82$ mm, $r_1 = 3.0$ mm, $r_2 = 29.09$ mm, $r_3 = 15.5$ mm, $h_0 = 27$ mm, $h_1 = 1.6$ mm, $h_2 = 19.9$ mm.

B. CIRCULAR POLARIZATION OPERATING PRINCIPLE

The CP operation of conventional crossed-dipole antennas were previously presented in [19]. As mentioned above, the proposed antenna exhibits a widen AR BW mainly due to the shape of the cross-dipoles and the stepped ground. Different from traditional cross-dipoles, the fan-shaped cross-dipoles have the advantages of expanding the bandwidth due to its conical structure. The fan-shaped cross-dipoles can excite two CP fields along the chord and the arc of them, respectively. The coupling between the cross-dipoles and the parasitic patches can generate additional CP band. Current distributions of the main parts of the antenna are shown in Fig.2.

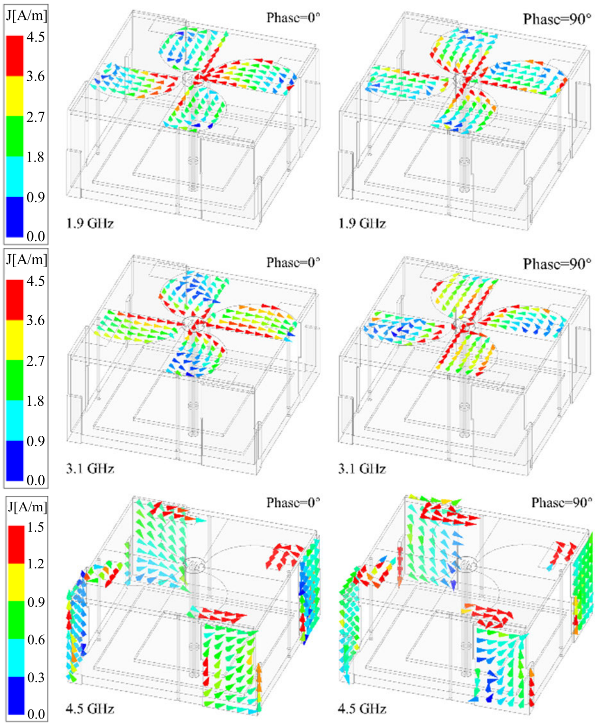


FIGURE 2. Current distributions of the main parts of the antenna.

As observed from Fig.2, two CP fields are realized by the current induced by the cross-dipoles. In both CP bands, the E-field rotates by 90° in clockwise direction when the phase changes from 0° to 90°. The main CP operating band is produced by the current on the chord of the cross-dipoles. The second CP operating band is generated by the current on the arc of the cross-dipoles. It can be seen from Fig.2 that the current flows on the cross-dipole in the tangent of the arc curve. Thus, the current flowing on the arc of the nearby cross-dipole is in the orthogonal direction. Since the length of the current on the arc of the cross-dipoles is longer than the former, the second CP operating band is lower.

The high CP fields are mainly generated by the coupling between the parasitic patches and the stepped ground, as shown in Fig. 2. The coupling current on the parasitic patches can be further equivalent to two orthogonal magnetic dipoles along the ±45° diagonal directions. The distributed current on the plates and posts can balance the current amplitudes and increase the resonant path.

C. ANTENNA WITH NON-PLANAR REFLECTOR

The antenna's performance can be enhanced by using a cavity-backed reflector as the additional radiator in [20]. The main principle is that the coupling radiating aperture is formed by the cavity-backed edges when the main radiator is excited. In this article, to reduce the high-profile of the cavity-backed reflector, we have utilized a stepped ground. To examine this, a planar ground and a stepped ground with the same size is radiated by one plane electromagnetic wave, respectively.

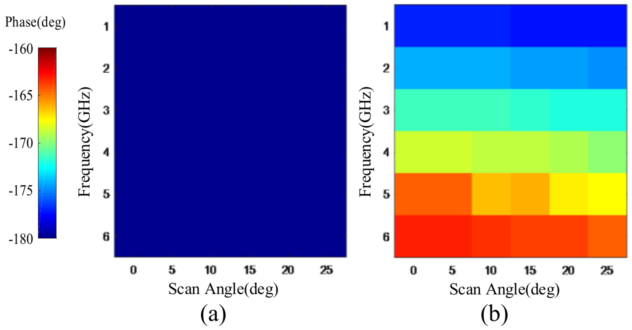


FIGURE 3. Numerically computed reflection phase of the planar ground and the stepped ground. (a) planar ground. (b) stepped ground.

As shown in Fig.3, the reflection phases of the planar ground almost keep constant no matter the scan angle or frequency varying in a certain range. In contrast, the reflection phases of the stepped ground have a large change at different frequencies. It also has an obvious impact on the reflection phase when the scan angle changes.

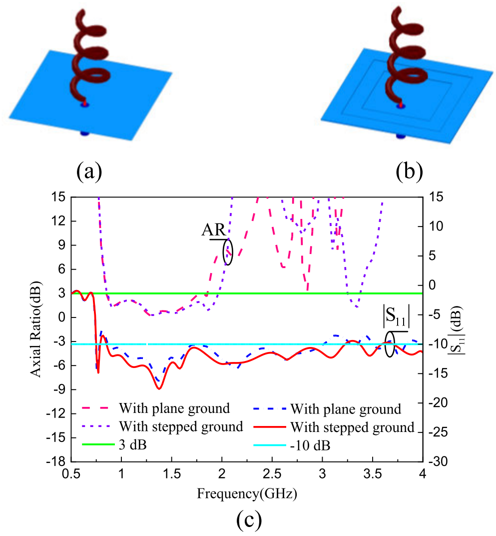


FIGURE 4. The continuous tapered-helix antenna with planar ground and with stepped ground. (a) Antenna with planar ground. (b) Antenna with stepped ground. (c) Simulated performance of two antennas.

In order to further verify such phenomenon, a continuous tapered-helix antenna is designed, as shown in Fig.4. Two similar size metal grounds are used as the helix antenna reflector. One is planar ground, and the other is stepped ground.

Simulated ARs and reflection coefficients of two antennas are presented in Fig.4 (c). Comparisons of two types of ground verify that the ARs and reflection coefficients is enhanced when the antenna with stepped ground, especially in the higher frequency band.

Fig.5 (a)∼(c) shows the comparison results between the rectangular cross-dipole antenna (Antenna I) and the fan-shaped cross-dipole antennas (Antenna II, III, Prop.). All the antennas use cross-dipoles, four parasitic patches, four plates, and have the same height. Different from the proposed

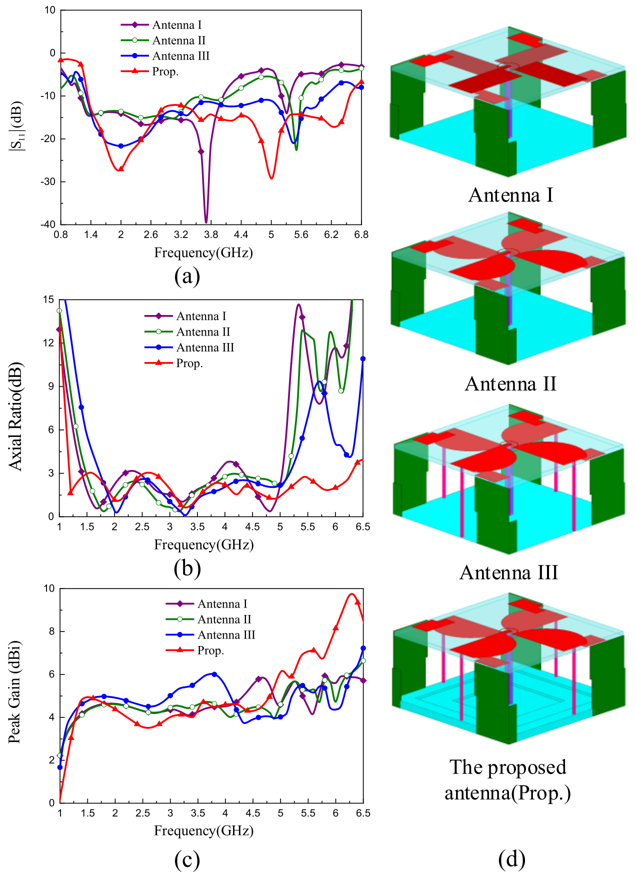


FIGURE 5. **The comprehensive comparison of four methods to improve the performance of the CP radiation. (a). Reflection coefficients. (b). ARs. (c). boresight gains. (d). The perspective view of the four antennas.**

antenna, a stepped ground is not used in Antenna I, Antenna II and Antenna III. Configuration of these antennas are shown in Fig.5 (d).

As shown in Fig.5, Antenna II exhibits a better performance in terms of impedance BWs and AR BWs compared with Antenna I, since the fan-shaped cross-dipole was utilized. However, the comparison results indicate that the boresight gain of Antenna II has a similar performance as Antenna I. Antenna III is with the four metal posts compared with the Antenna I, II. For antenna III, one arm of the cross-dipole, a metal post, a coaxial cable and the planner ground can be considered as a circuit loop. Through a proper adjustment of the size and position of the posts, the CP performance could be improved, which has been shown in Fig.5. The plates are welded on the stepped ground which can substitute the height weight of surrounding back-cavity. In addition, too many layers of the stepped ground will increase the complexity of the design process. After careful analysis and optimization, when the number of layers is 3 and the size is the same as that of the antenna substrate, it has good performance.

Without profile increasing, both a widen impedance BW and AR BW can be realized when the stepped ground is utilized by the proposed antenna. Fig.5 also demonstrates that the broadside gain of the proposed antenna at the higher frequency is improved than the others. Such a combination of the stepped ground and the plates is an effective method to expand the wideband and realize a gain improvement.

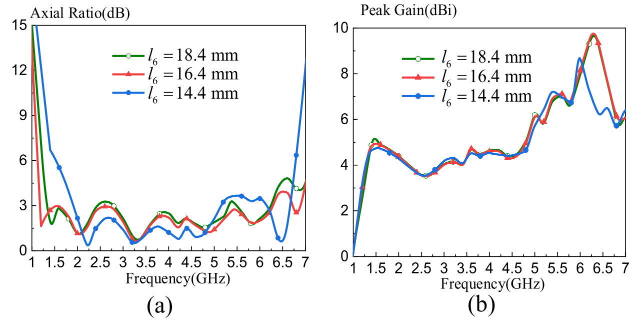


FIGURE 6. **(a) ARs and (b) Gains under different l_6.**

D. PARAMETERS ANALYSIS

To further investigate the coupling effect of the L-shaped parasitic patches and fan-shaped cross-dipoles. The CP performances for different values of l_6 and w_1 are shown in Fig.6. Seen from Fig.6, when the value of l_6 =16.4 mm, the antenna operation achieves the wider AR BW and highest gain in the frequency range of 6-7 GHz. Besides, the width of the Z-shaped plates(w_1) has an impact on the impedance BW and AR BW, which is demonstrated in Fig.7. By choosing a proper size, a very wide AR BW is obtained. When w_1 increases, the middle resonant band of the impedance would shift downwards and the impedance BW increases until w_1 reaches an optimum value. Meanwhile, the performance of the AR BW has a remarkable change in the lower band and the middle band. For w_1 = 17 mm, the AR BW achieves a wideband operation in a corresponding impedance BW. Thus, the value of w_1 = 17 mm is set as the optimum value for the design.

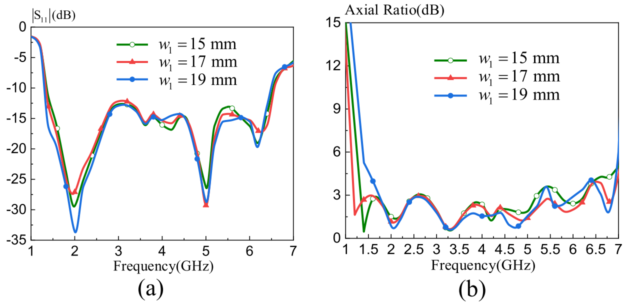
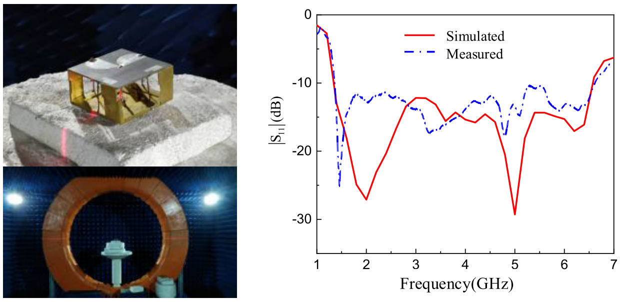


FIGURE 7. **(a) Reflection coefficients and (b) ARs under different w_1.**

III. RESULTS AND COMPARISON

A. MEASURED AND SIMULATED RESULTS

To verify broadband CP, a prototype of the proposed fan-shaped cross-dipoles antenna was designed, fabricated, and tested. Fig.8 (a) shows the antenna prototype, and the simulated and measured reflection coefficients of the prototype are shown in Fig.8 (b). From Fig. 8(b), the measured reflection



(a) (b)

FIGURE 8. (a) The antenna prototype. (b) Simulated and measured reflection coefficients.

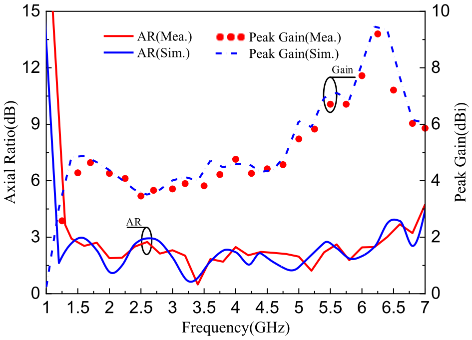
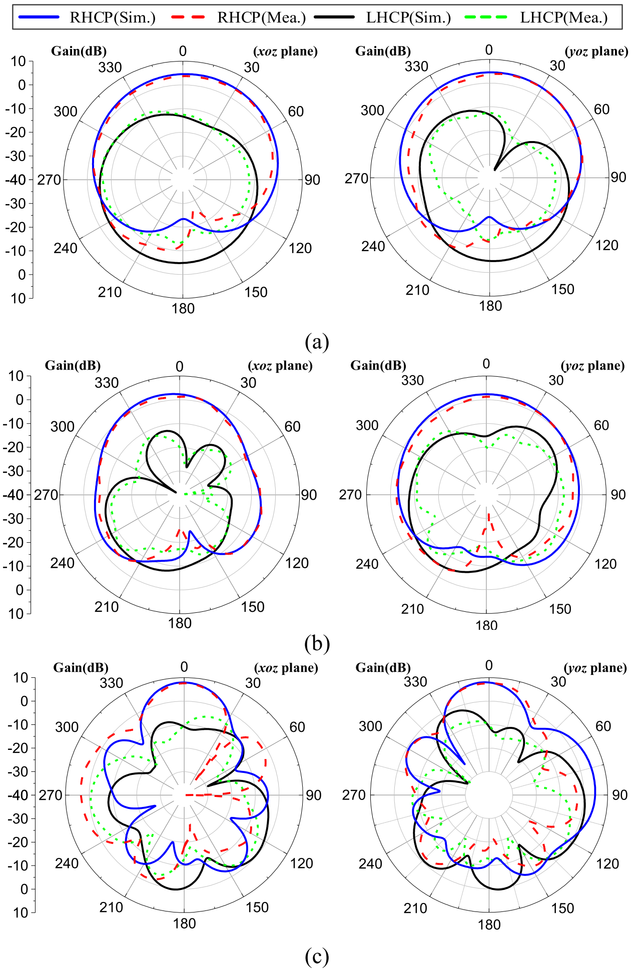


FIGURE 9. Simulated and measured ARs and peak gains.

TABLE 1. Comparison between the proposed antenna and other CP cross-dipoles designs.

Ref	Size(λ_l^3)	Impedance BW	AR BW	Peak Gain
[1]	0.28 × 0.28 × 0.11	0.84-3.12 GHz (115.2%)	0.92-3 GHz (106.1%)	7.0 dBi
[3]	0.56 × 0.56 × 0.19	1.9-3.9 GHz (68.9%)	2.05-3.75 GHz (58.6%)	9.4 dBi
[9]	0.57 × 0.57 × 0.24	1.8-4.6 GHz (79.4%)	2.0-4.0 GHz (66.7%)	9.7 dBi
[10]	0.42 × 0.42 × 0.23	1.99-3.22 GHz (50.2%)	2.30-2.9 GHz (27%)	6.8 dBi
[15]	0.96 × 0.96 × 0.09	3.64-7.3 GHz (66.9%)	4.12-7.25GHz (55.1%)	11.5 dBi
[17]	0.54 × 0.54 × 0.16	2-3 GHz (40%) 3.8-6.3 GHz (49.5%)	2.25-2.73 GHz (19.3%) 4.3-6.05 GHz (33.8%)	9 dBi
[21]	0.45 × 0.45 × 0.23	1.05-1.79 GHz (51.8%)	1.12-1.64 GHz (37.7%)	7.3 dBi
This work	0.27 × 0.27 × 0.12	1.36-6.65 GHz (132.08 %)	1.39-6.4 GHz (128.6 %)	9.45 dBi

coefficients are in good agreement with the simulated results. The measured results show that the antenna yielded a wide operation of 1.36-6.65 GHz (132.08 %), which is in accordance with the simulated result of 132.3%(1.34 to 6.58 GHz). Fig.9 depicts simulated and measured AR and peak gains in the boresight direction of the prototype. The measured 3-dB AR BW is approximately 128.6 % (1.39-6.4 GHz), close to the simulated AR BW 136.73% (1.18 to 6.28 GHz). The measured peak gain in such passband is 9.45 dBi. The measured patterns at frequencies of 1.5 GHz, 3.8 GHz and 6.0 GHz in both xz- and yz- planes are illustrated in Fig.10. As shown in Fig.10, the measured results agree well with simulations. Although the patterns are not ideally symmetric due to the asymmetrical feed, the cross-polarization levels still remain below −15 dB. If necessary, a larger ground reflector could be used and the better front-to-back ratio would be realized, while, it is beyond the research scope of this work.



(a)

(b)

(c)

FIGURE 10. Simulated and measured radiation patterns of the prototype. (a) 1.5 GHz (b) 3.8 GHz (c) 6.0 GHz.

B. WIDEBAND PERFORMANCE COMPARISON OF THE ANTENNA AND OTHER PREVIOUS DESIGNS

The comparisons of the proposed antenna with the recent proposed cross-dipole antennas are summarized in Table 1. In Table 1, the proposed antenna shows a salient performance regardless of the considerable volume reduction and the greatly improvement of impedance and AR BW, compared with other antennas.

IV. CONCLUSION

In this article, a broadband CP antenna with non-planar reflector is presented. By the use of the cross-dipoles with parasitic patches, the stepped ground, four plates and four mental posts, the proposed antenna yields a low profile, good impedance matching, and wider 3-dB AR BW. Through designing a proper reflector, the reflection phases can be changed, which can produce a wideband CP band and improve the broadside gain. To verify broadband performance, a prototype has been fabricated and measured.

The proposed antenna achieves −10-dB impedance bandwidth of 1.36-6.65 GHz (132.08 %), as well as 3-dB AR BW of 1.39-6.4 GHz (128.6 %), showing the antenna has a prominent broadband performance. In addition, the measured radiation fields of the antenna have a RHCP in the boresight direction.

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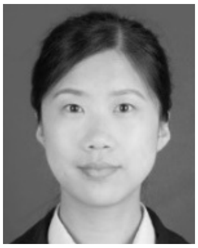

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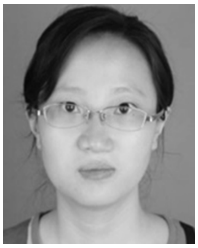

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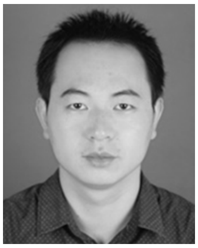

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