Broadband Circularly Polarized Antenna With Non-Planar Reflector

ZHANBIAO YANG1, JIANHUI BAO2, WENTAO LI1, (Member, IEEE), BEI LIU3, (Student Member, IEEE), HAO WANG4, LE KANG5, AND XIAO-WEI SHI1, (Senior Member, IEEE)

1Science and Technology on Antenna and Microwave Laboratory, Xidian University, Xi’an 710071, China
2School of Electronics and Information Engineering, Hebei University of Technology, Tianjin 300401, China
3School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798
4China Academy of Space Technology, Xi’an 710100, China
5School of Mechano-Electronic Engineering, Xidian University, Xi’an 710071, China

Corresponding authors: Xiao-Wei Shi (xwshi@mail.xidian.edu.cn) and Zhanbiao Yang (zhanbiaoyang@stu.xidian.edu.cn)

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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 0.27λl × 0.27λl × 0.12λl (where λl 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].
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 $0.27\lambda\times 0.27\lambda\times 0.12\lambda$. 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 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.

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.
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.

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.

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
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 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.

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

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
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.

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

| Ref | Size($\lambda_i$) | 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%) | 4.12-7.25 GHz (55.1%) | 11.5 dBi |
| [17] | 0.54 × 0.54 × 0.16 | 2-3 GHz (40%) | 2.25-2.73 GHz (19.3%) | 9 dBi |
| [19] | 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 |

### 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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ZHANBIAO YANG was born in Henan, China. He is currently pursuing the Ph.D. degree with the School of Electronic Engineering, Xidian University, Xi’an, China.

His research interests include design and optimization of antennas, co-optimization for microwave circuits and antennas, wideband antennas and arrays, and parallel or distributed optimization techniques.

JIANHUI BAO was born in Heilongjiang, China, in 1987. She received the B.S. degree in electronic engineering and the Ph.D. degree in electromagnetic field and microwave technology from Xidian University, Xi’an, China, in 2010 and 2016, respectively.

She is currently a Lecturer with the School of Electronics and Information Engineering, Hebei University of Technology, Tianjin, China. Her current research interests include flexible electronic devices, millimeter-wave antennas, and antenna arrays.

WENTAO LI (Member, IEEE) was born in Shaanxi, China. She received the B.S. degree in electromagnetic engineering and the Ph.D. degree in electromagnetic fields and microwave technology from Xidian University, Xi’an, China, in 2006 and 2010, respectively.

She is currently an Associate Professor with the School of Electronic Engineering, Xidian University. Her current research interests include evolutionary optimization techniques, antenna arrays, and ultra-wideband antennas.
BEI LIU (Student Member, IEEE) received the B.E. degree in electric and information engineering from Northwestern Polytechnical University (NWPU), Xi’an, China, in 2009, the M.S. degree from Xidian University, Xi’an, in 2012, and the Ph.D. degree from Nanyang Technological University (NTU), Singapore, in 2020. From 2012 to 2014, he was with the State Radio Monitoring Centre, China, where he focused on signal analysis, spectrum allocation, and radio monitoring technique. He currently works as a Research Fellow with the VIRTUS, IC Design Centre of Excellence, Nanyang Technological University. His current research interests include CMOS power amplifier and transceiver, and GaN monolithic microwave integrated circuit (MMIC) power amplifiers for wireless communication.

HAO WANG was born in Hubei, China. He received the Ph.D. degree in electrical engineering from Xidian University, Xi’an, China, in 2016. He is currently an Engineer of antenna design with the Xi’an Institute of Space Radio Technology (XISRT), Xi’an. His current research interests include microwave/millimeter-wave antennas, reflectarray antennas, and satellite antenna design.

LE KANG received the B.S. and M.S. degrees from Xidian University, China, in 2008 and 2011, respectively, and the Ph.D. degree in electromagnetic field and microwave technology from the National Key Laboratory of Antennas and Microwave Technology, Xidian University, in 2017. From 2011 to 2012, he was an RF Engineer with Huawei Company, China. He is currently a Lecturer with the School of Mechano-Electronic Engineering, Xidian University. His current research interests include reconfigurable antennas and phased arrays.

XIAO-WEI SHI (Senior Member, IEEE) was born in Guangdong, China, in 1963. He received the B.S. degree in radio physics, the M.E. degree in electrical engineering, and the Ph.D. degree in electromagnetic field and microwave technology from Xidian University, Xi’an, China, in 1982, 1990, and 1995, respectively. From 1996 to 1997, he was a Postdoctoral Fellow with the Electronics and Telecommunications Research Institute, Daejeon, South Korea. He has been a Professor and a Ph.D. Student Advisor with Xidian University. His current research interests include the theory of microwave networks, microwave measurement, electromagnetic inverse scattering, and the theory of electromagnetic variation, electromagnetic compatibility, and smart antenna.