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An Ultra-Wideband Circularly Polarized Asymmetric-*S* Antenna With Enhanced Bandwidth and Beamwidth Performance

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ABSTRACT This paper introduces an ultra-wideband circularly polarized (CP) asymmetric-*S* antenna with wide axial ratio beamwidth (ARBW) for C-band applications. The proposed antenna is realized by bending a linearly polarized dipole into asymmetric-*S* shape with variable trace width, which achieves CP radiation. Unlike the reported symmetric-*S* antenna, the proposed antenna is constituted with two unequal curved arms to enhance the bandwidth and beamwidth performances. Compared with the symmetric-*S* antenna, the proposed antenna demonstrates much wider AR bandwidth and wider ARBW over broader frequency range. A prototype is fabricated to verify the design principle. The measured and simulated results are very consistent and both indicate that the proposed antenna has a wide impedance bandwidth (VSWR < 2) of 70.2% (3.58 to 7.46 GHz), and a wide 3-dB AR bandwidth of 84.8% (2.75 to 6.8 GHz). Moreover, maximum ARBW of 153° is achieved, and a 3-dB ARBW of more than 100° is maintained within a wide operation bandwidth of 46.3% (3.65-5.85 GHz).

INDEX TERMS Circularly polarized antenna, wide axial ratio beamwidth, ultra-wideband antenna.

I. INTRODUCTION

Due to the advantages of the mitigation of multipath fading and immunity of polarization mismatching, the circularly polarized (CP) antennas are widely used in wireless systems, such as the global positioning system (GPS) [1], radio frequency identification (RFID) [2] and wireless local network (WLAN) [3]. In recent decades, extensive research works on improving the axial ratio (AR) bandwidth of CP antennas were reported. Wideband cross-dipole antennas with good AR performance were proposed [4]–[6]. In [4], the width of the cross-dipole arms was properly widened to obtain the wide 3-dB AR bandwidth. Further, by adding parasitic elements nearing the cross-dipole arms, a wider 3-dB AR bandwidth was obtained [5], [6]. Other antennas, such as the stacked patch antenna [7], the sequentially rotated microstrip patch antenna array [8], and the hybrid dielectric resonator antenna [9], [10], are also good candidates for wideband CP operation.

Apart from the wide CP operation bandwidth, CP antennas with wide axial ratio beamwidth (ARBW) are also preferred, especially for the global navigation satellite system (GNSS) to secure stable communication links [11], [12]. A circular microstrip patch antenna coupled by a microstrip feed-line through a modified L-shaped aperture slot could achieve a wide ARBW of 190° from 27.5 to 30.1 GHz (9%).

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Nonetheless, its AR bandwidth was relatively narrow (12.2%) [13]. It was demonstrated that a wide ARBW of about 130° could be obtained by using a metallic cavity instead of the traditional planar ground plane [14]. In addition, combining magneto-electric dipole with crossed dipoles also led to a wide ARBW [15], [16]. In [15], a 3-dB ARBW of about 162° within the frequency range of 1.85 to 2.25 GHz (19. 5%) was achieved, and a 3-dB ARBW of 165° was realized from 1.45 to 1.75 GHz (15. 8%) in [16]. In [17], a wideband magneto-electric dipole with 32.8% AR bandwidth was reported, and over 85° ARBW could be realized from 1.85 to 2.1 GHz (15.4%). Nevertheless, most of the aforementioned antennas maintain wide ARBW within a relatively narrow frequency range.

In this paper, we propose a novel asymmetric-*S* antenna, which has ultra wide AR bandwidth and wide ARBW simultaneously. The proposed asymmetric-*S* dipole antenna is designed with two unequal-length curved arms, which improves both the AR bandwidth and ARBW performance of the antenna. Compared with the symmetric-S dipole [18], [19], the 3-dB AR bandwidth of the proposed antenna is increased from 42% to 84.8%, while the proposed antenna can keep a broad ARBW (>100°) over wider frequency range (from 35% to 46.3%). Moreover, maximum ARBW of 153° is achieved by the presented design while the symmetric-*S* antenna can realize 140° ARBW at most.

II. ANTENNA DESIGN AND ANALYSIS

A. ANTENNA GEOMETRY

Figure 1 shows the geometry of the proposed asymmetric-*S* antenna. As shown, the antenna consists of two unequal curved arms and is printed on the bottom layer of a Rogers RO4003C substrate with a size of $w_1 \times L_1$ and a thickness of 0.508 mm. Each arm of the proposed antenna can be obtained by subtracting a small ellipse from a bigger one. To feed the antenna, an integrated balun, which transforms the unbalanced microstrip feed to balanced slot line feed, is utilized. The balun is printed on both layers of a 0.813 mm thick Rogers RO4003C substrate which has a size of $w_1 \times H_1$. To obtain a unidirectional radiation pattern, a ground plane with $L_{rf} \times L_{rf}$ size is placed below the antenna at a distance of H_2. Optimal antenna performance can be achieved by choosing the proper distance between the antenna and the ground plane. As shown in Fig. 1 (b), the major axis radius of the four ellipses are denoted by R_i ($i = 1, 2, 3, 4$) while the minor axis radius is denoted by R_i/a. In addition, b denotes the ratio of R_1/R_2 and R_3/R_4. The two smaller ellipses are clockwise rotated along point O or O_1 with an angle of α and then are subtracted from the two bigger ellipses. Since the traveling wave current is excited along the curved arms, ultra-wideband CP radiation and wide ARBW can be realized. The detailed operating principle of CP radiation for such kind of antenna can be found in our previous work [18], [19] and is not presented here again for brevity. The optimal geometric dimensions of the proposed antenna are shown in Table 1.

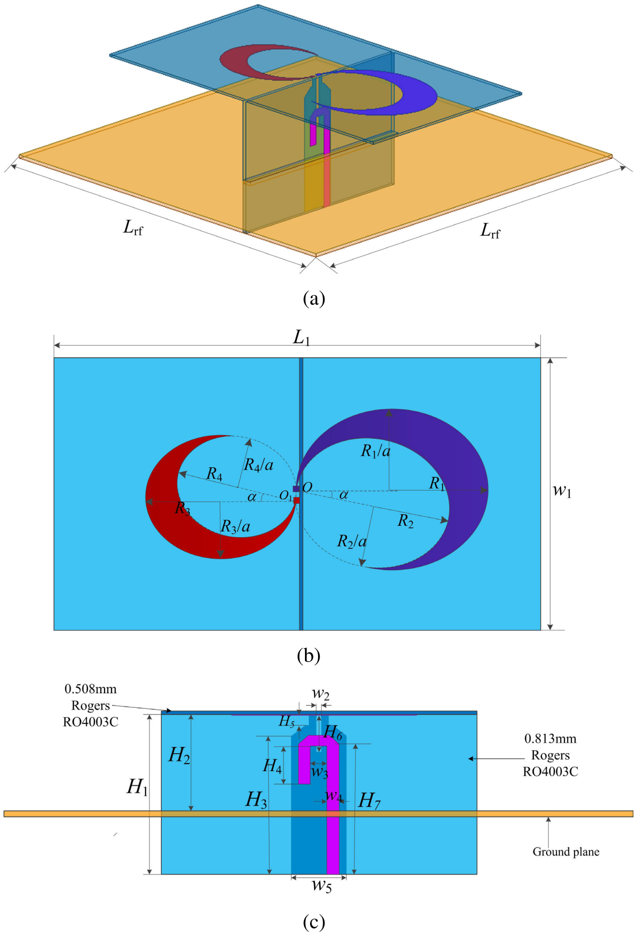


FIGURE 1. Geometry of the proposed antenna; (a) 3D view; (b) Top view of antenna radiator; (c) Side view.

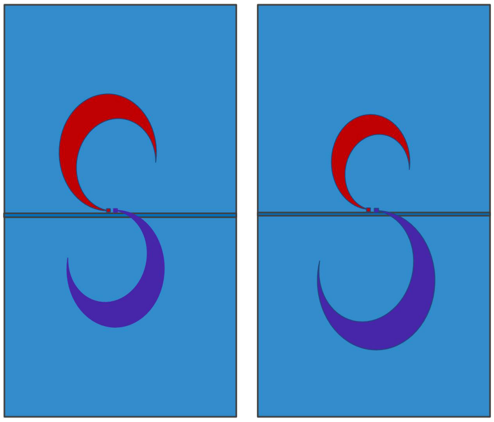

(a) (b)

FIGURE 2. (a) The reference antenna; (b) The proposed antenna.

B. THE MECHANISM OF PERFORMANCE IMPROVEMENT

To illustrate the advantages of the proposed design approach, a comparison between the symmetric-*S* antenna mentioned in [18] and proposed antenna is conducted in terms of bandwidth and beamwidth performance. Fig. 2 shows

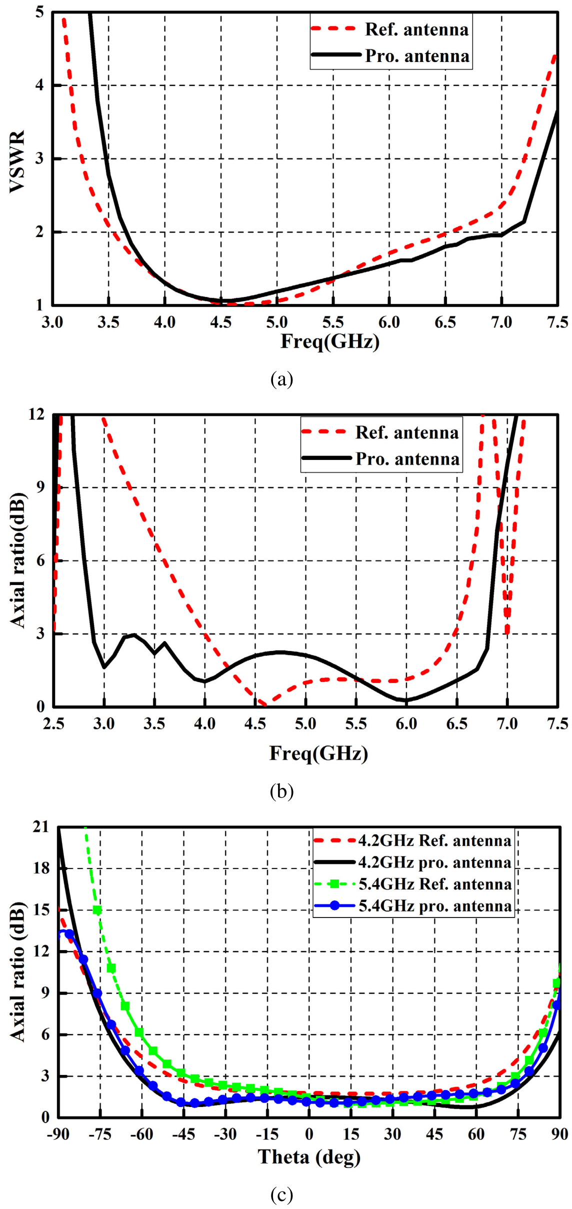


FIGURE 3. VSWR, AR and ARBW of the reference antenna and the proposed antenna. (a) VSWR, (b) AR, (c) ARBW.

TABLE 1. Antenna parameters (mm).

w_1	w_2	w_3	w_4	w_5	L_1	L_{rf}	R_1	R_2	α
45	0.8	2.46	1.8	8	80	90	16	10	10
a	b	H_1	H_2	H_3	H_4	H_5	H_6	H_7	
1.2	1.25	30	18	26	6.23	2	11.5	21.5	

the geometry comparison between the reference antenna (symmetric-*S* antenna) and the proposed antenna. As shown in Fig. 2, one arm of the proposed antenna is smaller than the arm of the reference antenna, while the other arm is larger than the reference antenna. The comparison between the reference antenna and the proposed antenna in terms of VSWR, AR, and ARBW performance are shown in Fig.3 (a), (b), and (c), respectively. As shown in Fig. 3 (a) and (b), the impedance bandwidth (VSWR $<$ 2)

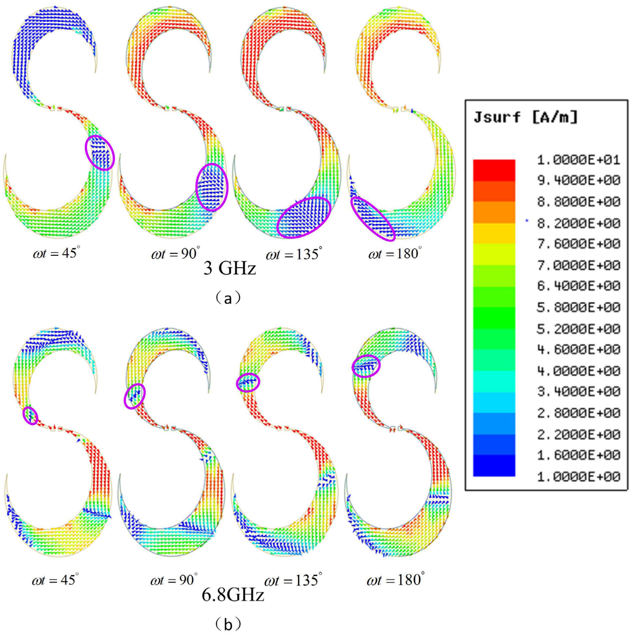


FIGURE 4. The surface current distribution on curved arms at different frequencies. (a) 3 GHz. (b) 6.8 GHz.

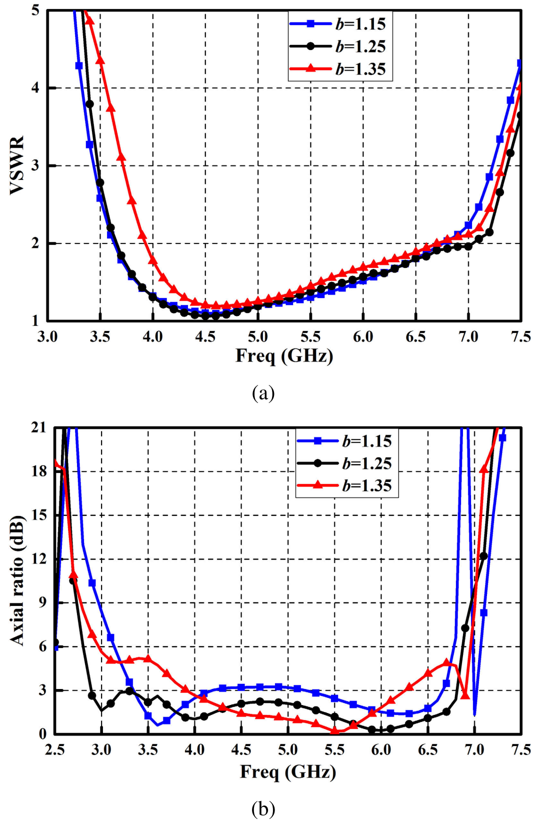
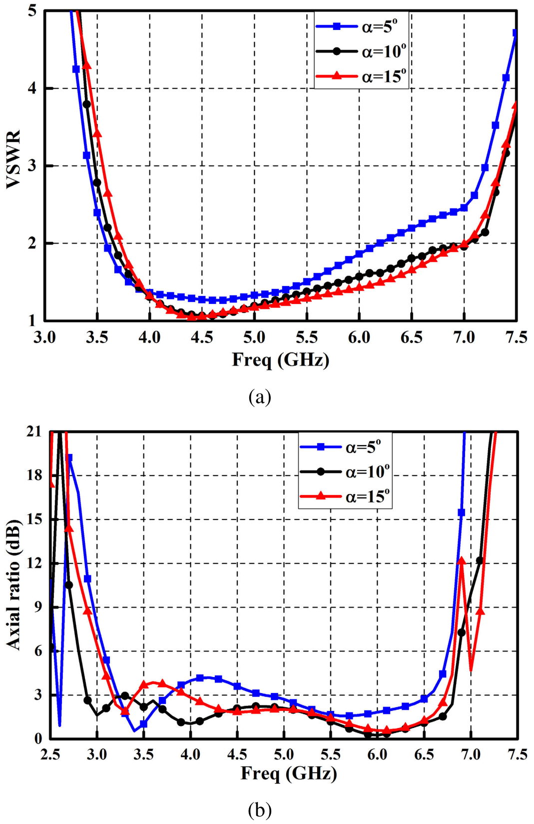


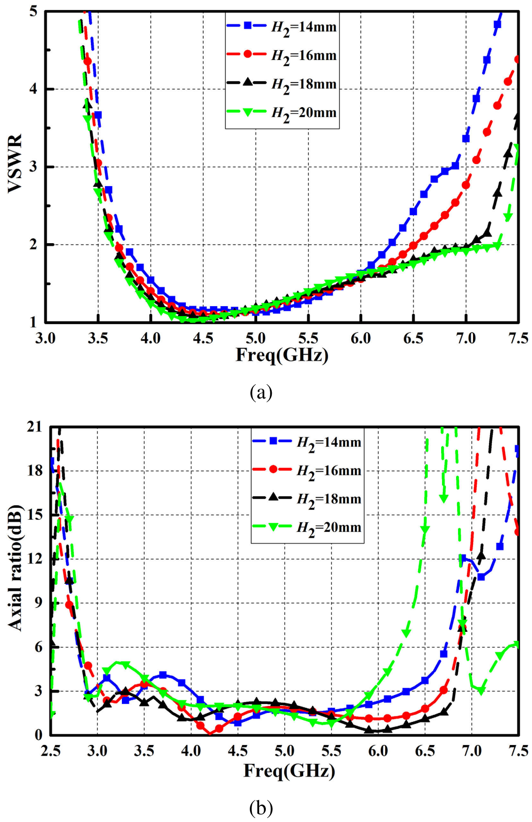
FIGURE 5. (a) VSWR and (b) AR with different values of *b*.



(a)

(b)

FIGURE 6. (a) VSWR and (b) AR with different values of α.



(a)

(b)

FIGURE 7. (a) VSWR and (b) AR with different values of H_2.

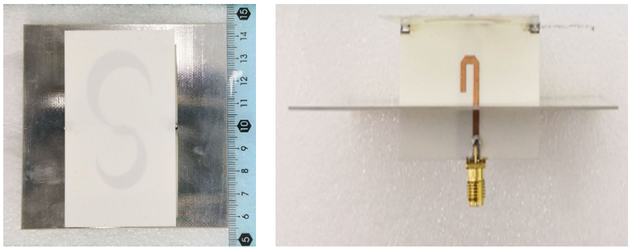
of the two antennas have slight differences, but the AR bandwidth of the proposed antenna is much wider. Considering that the smaller arm operates at higher frequency than the reference arm and the bigger arm operates at lower frequency than the reference arm, combing the two asymmetric arms together will extend the operating bandwidth towards higher frequency and lower frequency simultaneously.

To provide a more visualized explanation, the surface current distribution on the two unequal-length curved arms at 3 GHz and 6.8 GHz are plotted in Fig. 4. As illustrated in Fig. 4 (a), the null area of the surface current propagates along the bigger arm, indicating that a traveling-wave current is excited along the bigger arm at 3 GHz. According to [18],the excited traveling-wave current along a curved path is able to generate a CP radiation and thus the CP radiation can be achieved at 3 GHz. It is also noted that the traveling-wave current is not observed along the smaller arm at 3 GHz due to its insufficient electric length. As the electric lengths of the both arms of symmetric-*S* antenna are also insufficient to support the propagation of the traveling-wave current at 3 GHz, the symmetric-*S* antenna cannot radiate CP waves efficiently at 3 GHz. Similarly, at 6.8 GHz, the traveling-wave current is mainly excited on the smaller arm, and a good CP radiation is obtained. Without the aid of the smaller arm, traveling-wave current cannot be evoked by the symmetric-*S* antenna and thus poor CP radiation is realized at 6.8 GHz. The bandwidth of the proposed antenna can be increased by appropriately selecting the size of the two asymmetric arms. Furthermore, as shown in Fig. 3 (c), the ARBW of the proposed antenna is also larger than that of the reference antenna.

C. PARAMETRIC STUDIES TO THE PROPOSED ANTENNA

In order to obtain the optimum electrical performances of the proposed antenna, parametric studies are introduced into the design process. Considering the complexity of the antenna design, only several key parameters, such as the ratio b, the rotation angle α and the distance H_2, are studied in this subsection. The variations of these three parameters mainly contribute to the impedance bandwidth and AR bandwidth. Only one parameter is changed each time while others are fixed with the values shown in Table 1.

The effects of ratio b on the impedance bandwidth and AR bandwidth are plotted in Fig. 5. As shown, when the ratio b is increased, both the impedance bandwidth and AR bandwidth are extended. further increasing of b larger than 1.25 results in deteriorated bandwdith. According to the parametric study, the suitable value of the ratio b is 1.25. Fig. 6 illustrates the effect of the rotation angle α on the impedance bandwidth and AR bandwidth. It can be found that when the value of the rotation angle α is increased, the impedance bandwidth can be extended towards high frequencies. Meanwhile, the AR varies significantly with the variation of the rotation angle α.



(a) (b)

FIGURE 8. Prototype of the proposed antenna. (a) Top view, (b) side view.

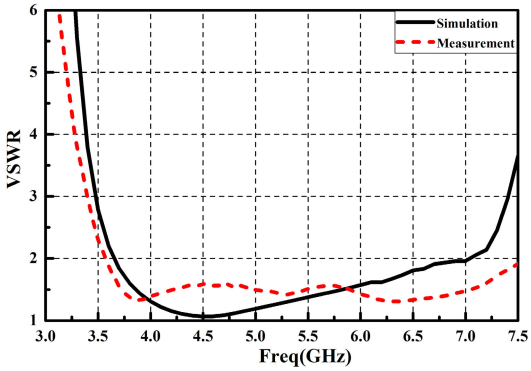


FIGURE 9. Simulated and measured VSWR of the proposed antenna.

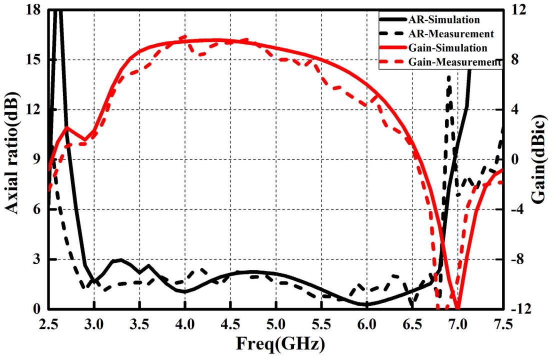
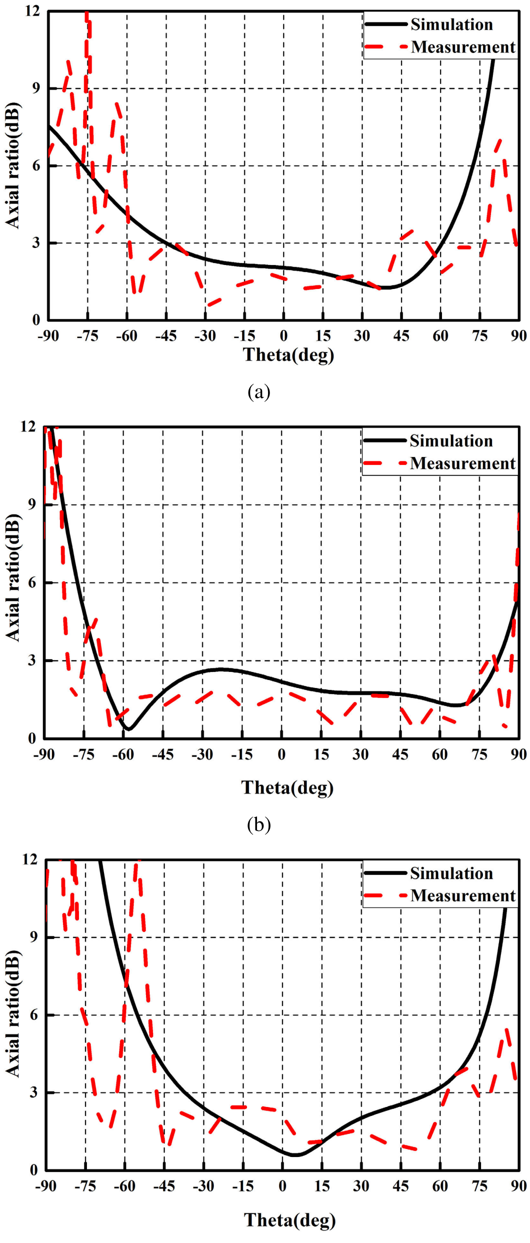


FIGURE 10. Simulated and measured AR and gain of the proposed antenna.



(a)

(b)

(c)

FIGURE 11. Simulated and measured ARBW in the xoz plane. (a) 3.7 GHz, (b) 4.6 GHz, (c) 5.7 GHz.

When $\alpha = 10^{\circ}$, the optimal AR performance can be obtained. Fig. 7 illustrates that as H_2 increases, the operating impedance bandwidth shifts upwardly. For AR, the optimal AR bandwidth is obtained when $H_2 = 18$mm. Further augment of H_2 leads to a degraded AR bandwidth.

III. RESULTS AND DISCUSSIONS

The proposed asymmetric-*S* antenna is fabricated and measured to verify the design principle. The fabricated prototype of the proposed antenna is shown in Fig. 8. The simulated and measured VSWRs of the proposed antenna are shown in Fig. 9. The measured impedance bandwidth is 70.2% for VSWR < 2, covering from 3.58 to 7.46 GHz. There is a certain deviation between the simulation results and measurement results, which may attribute to the fabrication and measurement errors. The simulated and measured ARs and gains are presented in Fig. 10. The measured 3-dB AR bandwidth is about 84.8%, from 2.75 to 6.8 GHz, which is consistent with the simulated result. As shown in Fig. 10, the measured gain is in good agreement with the simulation result, and the peak gain is 9.55 dBic at 4.5 GHz. Fig. 11 shows the simulated and measured ARBW in the *xoz* plane at different frequency points. As shown, the measured ARBW in the *xoz* plane is 115° at 3.7 GHz, 153° at 4.6 GHz and 105° at 5.7 GHz, respectively, which confirms that the proposed antenna maintains wide ARBW across a

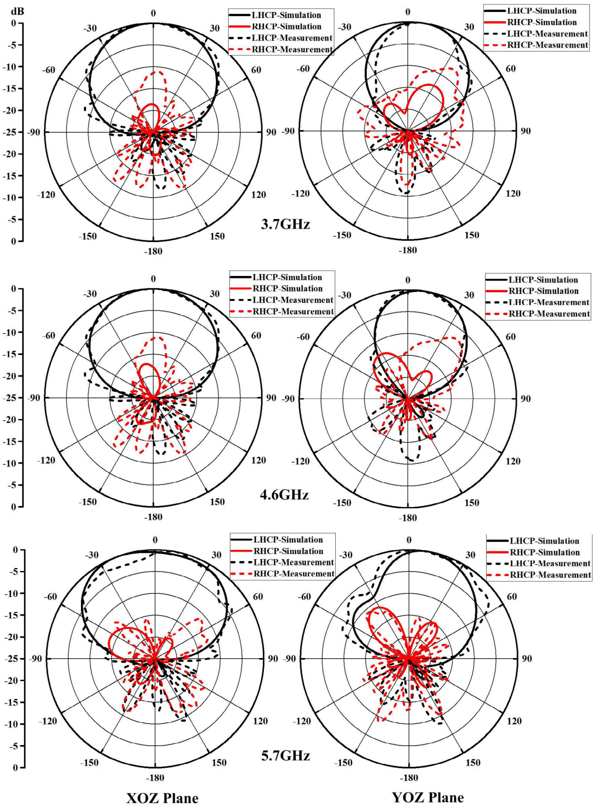


FIGURE 12. Simulated and measured radiation patterns of the proposed antenna in xoz plane and yoz plane.

TABLE 2. Comparison between the proposed antenna and other kinds of wideband and wide AR beamwidth CP antennas (λ_0 is the wavelength of center frequency).

Ref	Antenna Size (λ_0^3/mm^3)	Impedance bandwidth	AR bandwidth	Maximum ARBW (bandwidth)
[13]	$0.6\lambda_0 \times 0.6\lambda_0$ $\times 0.1\lambda_0$	13.8%	12.2%	190° (Beamwidth > 165°:9%) 27.5-30.1GHz
[15]	$0.64\lambda_0 \times 0.64\lambda_0$ $\times 1.16\lambda_0$	59.8%	26.8%	175° (Beamwidth > 165°:15.8%) 1.45-1.7GHz
[16]	$0.78\lambda_0 \times 0.78\lambda_0$ $\times 0.78\lambda_0$	72.1%	45.3%	237° (Beamwidth > 162°:19.5%) 1.85-2.25GHz
[17]	$1.0\lambda_0 \times 1.0\lambda_0$ $\times 0.25\lambda_0$	40.8%	32.8%	85° (15.4%) 1.8-2.1GHz
[18]	$1.52\lambda_0 \times 1.52\lambda_0$ $\times 0.31\lambda_0$	62.6%	42%	142° (Beamwidth > 100°:35.3%) 4.2-6GHz
This work	$1.44\lambda_0 \times 1.44\lambda_0$ $\times 0.29\lambda_0$	70.2%	84.8%	153° (Beamwidth > 100°:46.3%) 3.65-5.85GHz

wide frequency range. The radiation patterns of the proposed antenna in the *xoz* plane and *yoz* plane at 3.7, 4.6 and 5.7 GHz are shown in Fig. 12. The results show that in the upper hemisphere region, the measurement results agree well with the simulation results. The discrepancy in the back lobe is caused by the scattering and reflection of the cable, antenna holder and the positioner.

In order to demonstrate the advantages of the proposed antenna, a comparison with other reported wideband and wide ARBW CP antennas is conducted and shown in Table 2. It can be seen that the proposed antenna has a much wider AR bandwidth and overlapped bandwidth than its counterparts. Moreover, the proposed antenna can maintain a broad ARBW over much wider frequency range.

IV. CONCLUSION

An ultra-wideband asymmetric-*S* CP antenna with wide ARBW has been proposed, analyzed, and experimentally verified. The proposed antenna consists of two unequal curved arms, which helps enhance the AR bandwidth and ARBW performance. The proposed antenna achieves an impedance bandwidth (VSWR < 2) of 70.2% (3.58 GHz, 3.58-7.46 GHz), and 3-dB AR bandwidth of 84.8% (4 GHz, 2.75-6.8 GHz). Besides, a wide ARBW of more than 100° can be maintained within a very wide frequency band ranging from 3.65 to 5.85 GHz (46. 3%) and maximum ARBW of 153° is achieved at 4.5 GHz. Due to the ultra-wide bandwidth, wide AR beamwidth and stable beamwidth feature over a wide frequency range, the proposed antenna is suitable for high-precision GNSS systems and other relevant applications.

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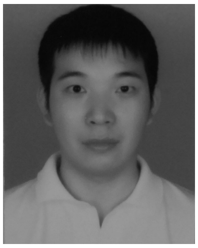

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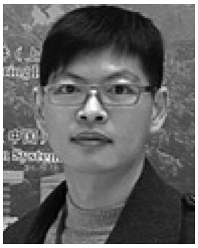

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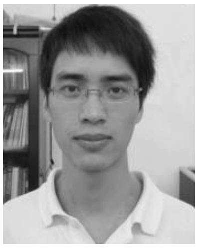

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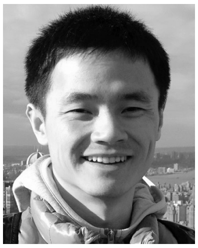

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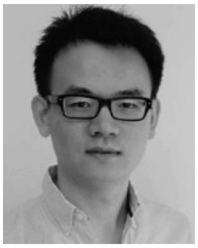

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