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Circular polarized patch antenna with wide 3-dB axial ratio beamwidth and suppressed backward cross-polarized radiation for high-precision marine navigation applications

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1 | INTRODUCTION

In global navigation satellite systems (GNSSs), circularly polarized (CP) antennas are very popular due to their advantages of suppressing multipath interference and reducing polarization mismatch. Thus, some CP antenna structures, such as cross-dipole [1], quadrifilar helix [2], and microstrip antennas [3], are widely investigated. Among them, the microstrip antenna has always been the research hotspot due to the advantages of low profile, light weight and low cost. For high-precision positioning, CP microstrip antennas are required to have high polarization purity, wide-angle circular polarization, symmetrical radiation pattern and superior multipath suppression [4]. Especially in marine navigation, CP microstrip antennas with a wider 3-dB axial ratio beamwidth (ARBW) are preferred for better reception of signals since ships often sway during voyage. Besides, anti-multipath performance is more critical for suppressing the interference from the sea-level reflection [5].

In recent years, numerous methods have been proposed to improve the 3-dB ARBW of CP microstrip antennas. Three-dimensional (3D) ground planes [6–8] and additional radiation elements [9, 10] have been regarded as effective methods. However, high profile and fabrication difficulty are inevitable. In [11], a suspended structure is proposed for determining the radiating area, but the antenna performance is very sensitive to the installation error of suspended height. In [12], the pin-loaded technique is utilized for a wide 3-dB ARBW. But the structure is not suitable for electrically small antennas and the 3-dB ARBWs become narrow when using finite ground. In [13], two pairs of narrow slots are inserted along the diagonal lines of a square patch for a wide 3-dB ARBW. In [14], the CP microstrip antenna with six metal columns is presented for wide-angle circular polarization. However, they all show narrow CP bandwidth (0.4% in [13] and 3.7% in [14]) which limits their applications.

Technologies for multipath suppression can be mainly classified into two categories, the high-impedance surface [15–19] and the reduced surface wave [20–22]. Among the high-impedance surfaces, the choke-rings [15–17] have been extensively used as successful commercial candidates. However, such antennas usually suffer from bulky volume and
heavy weight. Alternatively, the electromagnetic band gap (EBG) can also be used as a high-impedance surface [18, 19]. Although the profile and weight of the antenna are reduced, the need of extreme multi periodicity results in large size. The reduced surface wave technique is first proposed in [20] and has been successfully applied to GPS antennas with low multipath [21, 22]. However, since anti-multipath is the only concern, the 3-dB ARBWs of these antennas are narrow.

The anti-multipath performance and 3-dB ARBWs of CP antennas are often researched separately in reported studies and they are rarely carried out in the joint design. In [5], pin-loaded CP microstrip antenna with a sharp gain roll-off and wide 3-dB ARBW is presented for reducing the undesired multipath interference. The measured gain-off is 20 dB and the 3-dB ARBW reaches 140°. However, for high-precision marine positioning, the 3-dB ARBW of more than 200° is preferred since the ship sways during voyage. Besides, since multipath interference is mainly induced from the primary reflection of the sea surface and is often received from the backward of the antenna, CP antennas with suppressed backward cross-polarization are critical. In [4], the dual-ground structure is proposed for suppressing the back radiation and simultaneously an increase in the 3-dB ARBW. The optimized front-back ratio (FBR) and 3-dB ARBW are 21 dB and 220°, respectively. However, a narrow CP bandwidth (0.25%) limits its application.

Here, a CP patch antenna with a wide 3-dB ARBW and suppressed backward cross-polarized radiation is proposed for high-precision marine positioning. It comprises a circular radiation patch, an annular metal strip, a circular row of L-shaped bent metal branches, a slot-loaded ground, shorting pins, and the quadrature feed network. By using the L-shaped bent metal branches and the slot-loaded ground, a wide 3-dB ARBW with reduced backward cross-polarized radiation is realized. The measured results show that the 3-dB ARBW and the FBR are more than 230° and 26 dB, respectively. Besides, a peak gain of 4.36 dBi is obtained in the operating band. The study is organized as follows: Section 2 describes the structure of the proposed antenna. Section 3 presents the design procedure and parameter effects of the proposed antenna. The measured results are presented in Section 4, followed by a conclusion in Section 5.

2 | ANTENNA DESIGN

Figure 1 shows the structure of the proposed antenna in terms of the exploded view, the top view and the side view. It
comprises a circular radiation patch, an annular metal strip, a circular row of L-shaped bent metal branch, a slot-loaded ground, the shorting pins, and the quadrature feeding network. The circular radiation patch and the annular metal strip are etched on the upper surface of the substrate I (F4B, \( \varepsilon_{r1} = 3 \), \( \tan \delta_1 = 0.003, b_1 = 1.5 \) mm) with a radius of \( r_{\text{adv}} \).

The circular radiation patch has a radius of \( R_1 \), the annular metal strip has an outer radius of \( R_2 \), as shown in Figure 1(b). The gap between the radiation patch and the inner radius of the annular metal strip is termed \( s_1 \). The circular patch is directly fed by two orthogonal coaxial probes for producing CP waves.

To enhance the 3-dB ARBW of the CP antenna, a slot with a width of \( s_2 \) is loaded on the ground of the antenna, which is etched on the bottom surface of substrate I. It is observed from Figure 1(c) that the ground has an outer radius of \( R_3 \), and the distance between the slot and the centre of the ground is \( R_4 \). To suppress the cross-polarization at low elevations for a wider 3-dB ARBW, a circular row of shorting pins with a radius of \( 2 \) mm is inserted in the annular metal strip as depicted in Figure 1(a). The gap between the shorting pins is 30°.

To suppress the cross-polarization at the backward, a circular row of L-shaped bent metal branch is loaded on the annular metal strip. The L-shaped bent metal branch is composed of a bent cylinder branch and a horizontal cylinder branch. The diameter of the cylinder is \( d_1 \). The bent cylinder branch has an elevation angle of \( \alpha_1 \), a height of \( h_1 \) and a bent radius of \( l_2 \). The horizontal cylinder branch has a length of \( l_1 \). To provide signals with equal amplitude and orthogonal phase, the trans-directional (TRD) coupler [23] is etched on the bottom surface of substrate II, as shown in Figure 1(d). The parameters of substrate II are same as that of substrate I except that the radius of substrate II is \( R_3 \). To reduce the influence of the feeding network on antenna performance, a ground plane with a radius of \( R_3 \) is etched on the upper surface of substrate II.

**FIGURE 2** Design evolutions of the proposed antenna: (a) Structure I, (b) Structure II, (c) Structure III, and (d) Structure IV
3 | DESIGN PROCEDURES AND PARAMETRIC STUDY

3.1 | Design procedures of the proposed CP antenna

In this section, the contributions of the slot-loaded ground, the shorting pins and the L-shaped bent metal branches to the CP antenna's performance are studied by the simulator HFSS. Figure 2 shows the design evolution of the proposed CP antenna. Figure 3 shows the simulated ARBWs and normalized radiation patterns of different structures. Simulations are done using the circular patch combined with the different structures. The feature of the feeding network is not considered. The evolution starts from Structure I (see Figure 2(a)), in which a ground plane is located below the radiator. The initial size of the ground plane is simulated in consideration of the widest 3-dB ARBW. After optimization, the size is assigned as 65 mm.

To enhance the 3-dB ARBW, a slot is loaded on the ground (named as Structure II) as shown in Figure 2(b). Due to the insertion of the slot, the ground plane in Structure I is divided into two parts, the smaller ground plane and the annular metal strip. The annular metal strip serves as a parasitic radiator on the ground, which will affect the ARBW of the main radiator. It is observed from Figure 3(a) that the 3-dB ARBW for Structure I is 145°, and it is increased to 160° by using Structure II. However, Structure II has less influence on the cross-polarization suppression at the back. It is shown in Figure 3(b) that the FBR for Structures I and II are 17.5 and 16.3 dB, respectively. To suppress the cross-polarization at a low elevation for a wider 3-dB ARBW, an annular metal strip is first etched on to the upper surface of Substrate I and a circular row of shorting pins is inserted to connect the metal strips on both sides of the substrate as Structure III depicted in Figure 2(c). It is shown in Figure 3(a) that the cross-polarization at low elevation angles is reduced and the 3-dB ARBW for Structure III is increased to 235°. However, the FBR is reduced to 14.1 dB. To suppress the backward cross-polarization, a circular row of L-shaped bent metal branch is loaded on the annular metal strip (named as Structure IV, see Figure 2(d)). As shown in Figure 3, the FBR is obviously increased to 25.3 dB and the 3-dB ARBW reaches 275°.

Since the antenna is fed by two orthogonal probes, two sets of orthogonal TM_{11} modes can be generated and contribute to circular polarization. Since the AR can be expressed as

\[ \text{AR}(\theta, \phi) = 20 \log_{10} \left[ \frac{E_{\theta}(\theta, \phi)}{E_{\phi}(\theta, \phi)} \right] \]

a wide 3-dB ARBW can be required when \( E_{\theta} \) and \( E_{\phi} \) have close intensity over a wide angular range. To further clarify the internal mechanism, the electric-fields in terms of amplitude and phase differences of \( E_{\theta} \) and \( E_{\phi} \) are shown in Figure 4. It is observed that compared to Structures I–III, the Structure IV produces a wider angular coverage of 90° phase difference with a similar magnitude difference, so that a wider ARBW is obtained. Moreover, since an

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**Figure 3** The simulated results of different structures at 1.575 GHz: (a) ARBWs and (b) normalized radiation patterns. ARBW, axial ratio beamwidth

**Figure 4** The simulated magnitude- and phase-differences of \( E_{\theta} \) and \( E_{\phi} \) for different structures at 1.575 GHz.
obvious jump of magnitude difference and a more unbalanced phase difference is revealed at the back of Structure IV, a more reduced backward cross-polarized radiation is realized.

### 3.2 | Parametric study of the proposed CP antenna

Based on the above evolution, the radiations of the CP antenna are mainly affected by two structures, the slot on the ground and the L-shaped bent metal branch. In this section, the parameters of the two structures are analysed in detail. When one parameter is studied, the others remain unchanged.

1. **Effect of the slot width $s_2$ and slot location $R_4$**: The effect of the slot width $s_2$ and slot location $R_4$ is investigated in this subsection. Figure 5 shows the 3-dB ARBW and the FBR of the antenna at the resonate frequency under various slot widths. As $s_2$ increases from 0 to 3 mm, the 3-dB ARBW rises from 221° to 265° with some ripple. As $s_2$ increases from 3 to 6 mm, the 3-dB ARBW decreases from 265° to 248°. Larger FBR can be observed when $s_2$ is in the range of 0.5–1.5 mm and 3.5–6 mm. After the trade-off in the 3-dB ARBW and the FBR, the optimized value of $s_2$ is selected as 3 mm. Figure 6 shows the 3-dB ARBW and the FBR under various slot location. It is observed that the 3-dB ARBW trends to increase when $R_4$ varies from 45 to 50 mm, and it decreases when $R_4$ varies from 50 to 55 mm.

**Figure 5** Effects of the slot width $s_2$.

**Figure 6** Effects of the slot location $R_4$.

**Figure 7** Effects of the branch length $l_1$.

**Figure 8** Effects of the branch length $l_2$.

**Figure 9** Effects of the branch height $h_1$. 

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While the FBR is distributed and stable in the range of 24–26 dB. In consideration of wider 3-dB ARBW, the value of $R_4$ is chosen as 50 mm.

2. Effect of the bent branch length $l_1$ and $l_2$: In addition to the slot, the dimensions of the L-shaped bent metal branch significantly affect the electromagnetic wave diffraction, which results in a different radiation performance. In this subsection, the effects of the bent branch length, $l_1$ and $l_2$, on the 3-dB ARBW and backward cross-polarized radiation are further investigated. As shown in Figure 7, when the length $l_1$ increases from 6 to 20 mm, the 3-dB ARBW's fluctuate in the range of 260–270° and the FBRs are in the range of 24.4–26.3 dB. After the trade-off in the 3-dB ARBW, the FBR and the dimension, the value of $l_1$ is selected as 10 mm. Figure 8 shows the influence of the length $l_2$. It is obvious that the effect of $l_2$ on antenna radiation performance are more than that of $l_1$. When $l_2$ rises from 18 to 39 mm, the 3-dB ARBW increases from 247° to 280°. While in the same range, a bidirectional curve is found in the FBR. Since a larger FBR is preferred, the value of $l_2$ chosen as 29 mm.

3. Effect of the bent branch height $b_1$, diameter $d_1$, and elevation angle of $\alpha_1$: Besides the length of the bent branch, the effects of the height $b_1$, diameter $d_1$ and elevation angle of $\alpha_1$ are also investigated. As shown in Figure 9, the height of the bent branch has less influence on the 3-dB ARBW of the antenna, but smaller height results in larger FBR. Thus, the height $b_1$ is chosen as 14 mm. Figure 10 shows the effects of the branch diameter. As $d_1$ rises from 2 to 18 mm, the 3-dB ARBW increases from 250° to 268° with some ripple. A bidirectional curve is exhibited for the FBR. For larger FBR, the value of $d_1$ is selected as 10 mm. Figure 11 shows the effects of the elevation angle $\alpha_1$. When $\alpha_1$ is smaller than

| Table 1 | Dimensions of the proposed antenna |
|---------|-----------------------------------|
| Parameter | $r_{cab}$ | $R_1$ | $R_2$ | $R_3$ | $R_4$ | $R_5$ | $s_1$ | $s_2$ |
| Value (mm) | 65 | 31.8 | 61 | 50 | 50 | 61 | 21.2 | 3 |
| Parameter | $l_1$ | $l_2$ | $l_3$ | $l_4$ | $l_5$ | $l_6$ | $\omega_1$ | $\omega_2$ |
| Value (mm) | 10 | 29 | 31 | 8 | 7.5 | 9.3 | 1 | 1.1 |
| Parameter | $\omega_{50}$ | $b_1$ | $d_1$ | $C_1$ | $R_1$ | $\alpha_1$ |
| Value (mm) | 2.8 | 1 | 10 | 2.2 pF | 50 $\Omega$ | 45° |

![Figure 10](image1.png) Effects of the branch diameter $d_1$.

![Figure 11](image2.png) Effects of the branch elevation angle $\alpha_1$.

![Figure 12](image3.png) The photograph of the fabricated antenna: (a) top view and (b) bottom view.
75°, the FBRs are larger than 25.1 dB. The 3-dB ARBW\text{s} are in the range of 257–268° when $\alpha_1$ changes from 45° to 75°. Thus, under the criterion of the 3-dB ARBW\text{s} >250° and FBR >25 dB, the range of $\alpha_1$ is 45–75°.

**Figure 14** Simulated and measured the results of the antenna: (a) $|S_{11}|$ and (b) gain and AR. AR, axial ratio

**Figure 13** Simulated results of the designed TRD coupler. TRD, trans-directional

**Figure 15** Simulated and measured normalized radiation patterns at 1.575 GHz: (a) $xoz$ plane and (b) $yoz$ plane

**Figure 16** Simulated and measured ARBW at 1.575 GHz. ARBW, axial ratio beamwidth
Considering a wider 3-dB ARBW, the value of $\alpha_1$ is selected as 45°. According to the above analysis, the dimensions of the antenna are determined and the values of all the parameters are shown in Table 1.

### 4 | IMPLEMENTATION AND MEASUREMENTS

For validation, a prototype has been fabricated, as shown in Figure 12. The L-shaped bent metal branches are composed of inner branches fabricated using a 3D printer and outer copper foils wrapped around the branches. The photopolymer resin ($\varepsilon_r = 3$, $\tan \delta = 0.019$) is used as the 3D-printed material. The TRD coupler is etched on the backside of the feeding circuit board. To reduce the effects of the coupler on the slotted ground of the antenna, an extra ground plane is etched on the front of the feeding circuit board. The radius $R_3$ of the added ground is assigned as 30 mm. According to the analysis in [23], the theory circuit parameters of the TRD coupler can be calculated, including the even-mode characteristic impedance ($Z_{eo}$) of 120.9 $\Omega$, the odd-mode characteristic impedance ($Z_{eo}$) of 77.2 $\Omega$, the electrical length ($\theta$) of 90°, and the capacitor ($C_l$) of 2.27 pF. After optimizing using the simulator HFSS, the final dimensions of the TRD coupler are obtained, as shown in Table 1 (corresponding to Figure 1(d)). Figure 13 shows the simulated results of the designed TRD coupler. It is seen that from 1.22 to 1.71 GHz (33.4%), the return loss of the designed TRD coupler is larger than 15 dB. For amplitude imbalance <1 dB, the simulated bandwidth is in the range of 1.38–1.69 GHz. At 1.575 GHz, the coupling and insertion loss of the TRD coupler are 3.19 and 3.09 dB, respectively. From 1.24 to 1.79 GHz, the output port phase difference is 90 $\pm$ 5°.

The feeding circuit board is tightly placed below the ground of the antenna. The measurements were taken using an Agilent N5230, vector network analyzer and an anechoic chamber. As depicted in Figure 14, good agreements are observed between the simulated and measured results of $|S_{11}|$, gain and AR. Under the criterion of $|S_{11}| < -10$ dB, the measured bandwidth is from 1.34 to 1.73 GHz (25.4%). The measured bandwidth for AR < 3 dB is from 1.52 to 1.60 GHz (5.1%). At 1.58 GHz, the measured gain is 4.36 dBi. Figure 15 shows the simulated and measured normalized radiation patterns of the fabricated antenna. It is observed that the patterns in the xoz and yoz planes are similar to each other, and the radiation patterns of RHCP is symmetric for the maximum radiation direction. In addition, the measured FBRs are more than 26 dB at xoz and yoz planes. Figure 16 shows the simulated and measured ARBW’s at 1.575 GHz. At the xoz plane, the measured 3-dB ARBW is 259°, and the value is 238° at the yoz plane. Table 2 shows the comparison of the proposed antenna with several representative antennas in the literature. Compared with the exhibited CP antennas, the proposed design shows better performance in terms of bandwidth, the 3-dB ARBW, and backward cross-polarized radiation, which can be used as a candidate for high-precision marine positioning applications.

### 5 | CONCLUSION

Here, a novel technique to achieve CP radiation with a wide 3-dB ARBW and suppressed backward cross-polarization has been presented. By inserting the slot on the ground of the antenna as well as loading the L-shaped bent metal branches, the 3-dB ARBW can be increased by more than 110° and the FBR can be enhanced by nearly 8 dB. To validate the simulation design, a prototype of the proposed CP antenna has been fabricated and measured. Experimental results show that the proposed antenna can achieve a bandwidth of 1.34–1.73 GHz for $|S_{11}| < -10$ dB, a bandwidth of 1.52–1.60 GHz for AR < 3 dB and a gain of 4.36 dBi. In particular, the measured 3-dB AR of the fabricated antenna at 1.575 GHz can cover a wide angular range of 259° and 238° at the xoz and yoz planes, respectively, with FBRs more than 26 dB. Therefore, the proposed CP antenna can be a desirable candidate for high-precision marine positioning applications.

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**Table 2** Comparison with several representative CP antennas

| Refs. | IBW (%) | CPBW (%) | FBR (dB) | 3-dB ARBW (°) | Dimension (L x H) |
|-------|---------|----------|----------|----------------|------------------|
| [4]   | 1.1     | 0.25     | 22.0     | 220            | $0.48 \lambda_0 \times 0.03 \lambda_0$ |
| [5]   | 2.4     | 0.6      | 18.0     | 138/136        | $0.92 \lambda_0 \times 0.013 \lambda_0$ |
| [10]  | 1.7     | 0.63     | 17.4     | >188           | $0.21 \lambda_0 \times 0.016 \lambda_0$ |
| [13]  | 3.4     | 0.96     | 18.8     | 226/198        | $0.29 \lambda_0 \times 0.013 \lambda_0$ |
| [14]  | 10.3    | 3.78     | 11.0     | 222/239        | $0.96 \lambda_0 \times 0.14 \lambda_0$ |
| [17]  | 20.8    | 8.5      | 13.8     | 190/193        | $0.45 \lambda_0 \times 0.064 \lambda_0$ |
| This work | 25.8 | 5.1    | 26.0     | 259/238        | $0.79 \lambda_0 \times 0.14 \lambda_0$ |

Note: $\lambda_0$ is the wavelength in air at the centre frequency. Abbreviations: ARBW, axial ratio beamwidth; FBR, front-back ratio.
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CONFLICT OF INTERESTS
The authors declare that there are no conflict of interests.

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