Novel circularly polarized slot array antennas with a wide 3-dB axial ratio bandwidth based on a spindle-shaped radiating cavity

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Abstract

A novel wide 3-dB axial ratio (AR) circularly polarized 2 × 2 array antenna is proposed in this paper. The spindle-shaped coupling cavity with tilted waveguide is capable of generating circular polarization waves from incident linear waves, which improves the AR bandwidth (ARBW) of the antenna. With this structure, a similar amplitude of the two orthogonal transmitted wave components and a stable phase difference of nearly 90° can be generated. The circularly polarized antenna proposed herein has been fabricated. According to the measurement results, the operating bandwidth from 5.32 to 6.13 GHz is < -10 dB. In addition, the measured ARBW, which is below 3 dB, can cover the range of 5.41–6.02 GHz. The maximum gain of the antenna can attain 15.65 dBi, and the efficiency is better than 80%.

Introduction

Circularly polarized antennas are critical for high-performance and low-loss antenna applications, such as uncompressed high-definition media transfers, sensing systems, and long-range high-resolution radar systems [1]. Circularly polarized antennas, offering desirable advantages such as flexibility, mobility, weather penetration, and reduction in multipath reflections in transmission and reception, will be employed more widely in these systems [2]. A waveguide slot antenna demonstrates the merits of high efficiency, low cost, and flexible mechanical assembly. To improve the operating bandwidth and radiation efficiency, the patch is covered on the waveguide slot antenna in [3], but the axial ratio bandwidth (ARBW) <3 dB is only 3%. In [4, 5], parasitic dipoles are placed above the gap to achieve circular polarization (CP). A major difference between [4] and [5] is that in [5] three parasitic patches are placed on the substrate waveguide. The antenna in [6] consists of a pair of loops fed by a slot and two square patches are added on the opposite corners of both loops to implement CP. In [7, 8], an antenna is filled with a dielectric material in the waveguide. The impedance bandwidth (IBW) and ARBW performance of the antenna can be effectively improved. However, the substrate loss will become worse with the increase in frequency and expansion of the array. The authors in [9] used a combination of slots with different lengths to expand the IBW and ARBW of the antenna, achieving a 21% wider ARBW, and a lower gain with seven elements. In [10], a circular polarizer is added to each slot of a waveguide slot antenna with a CP bandwidth of 2%. In [11], CP is realized by combining two orthogonal linear polarizations, which are generated by two pairs of radiation slots on a cavity surface. However, the ARBW of the antenna is only 1.2%. The circular polarizer is fed by a slot, but the ARBW is narrow in [12–14].

In this paper, we designed a wide-axis ratio antenna that can achieve CP. The antenna is an all-metal structure, which is relatively simple to process and of low cost. The adopted coupling cavity with a twisted waveguide effectively improves the CP axis ratio performance of the antenna. The three-dimensional model of the antenna is shown in Fig. 1.

CP unit cell design

In [15], a microstrip circularly polarized antenna is designed. The rectangular strips form an orthogonal current with a 90° time shift on the surface of the antenna. The structure composed of two symmetrical square-coupling cavities is designed in this paper, which can form an electric field with a 90° time shifted. The unit is shown in Fig. 2. A symmetric square-coupling cavity is placed on a waveguide (F1 × F2) and excited. The operating principle of the CP antenna is that two orthogonal electric field modes with equal amplitude but a phase shift of 90° can be obtained [16]. The symmetric square-coupling cavity is connected by two square-coupling
cavities, as shown in Fig. 2(a). However, the size of the configuration will not make the distance between the array elements less than one wavelength. The corners of the symmetrical square-coupling cavity are cut to improve the compactness of the antenna. Figure 2(b) shows a spindle-shaped coupling cavity. The comparison simulated results of $S_{11}$ and AR of the two structures are shown in Fig. 6.

The electric field of the waveguide is coupled to the symmetric square-coupling cavity, where it is decomposed into orthogonal electric fields with the same amplitude and 90° phase shift. Figure 3 shows the electric field of the unit cell operating at 5.8 GHz. The electric field density on the surface of the antenna for different phases of excitation field is simulated. When the phase of the excitation vector is 0° or 180° and 90° or 270°, which gives rise to radiation of waves polarized along the $x$-axis and $y$-axis and obtain the right-handed circularly polarized (RHCP) electric field.

To demonstrate the effects of these parameters, we analyzed the axial ratio (AR) of the antenna with different values of $L_r$ and $L_s$. The dependences of the AR on the different values at the lower frequency band and the higher frequency band are presented in Figs 4(a) and 4(b), respectively. If the value of $L_r$ is less than 0.6$\lambda_0$ (where $\lambda_0$ is the free-space wavelength at 5.8 GHz), the AR curve will be shifted. The AR performance will become worse when the value of $L_r$ is more than 0.6$\lambda_0$. The best value for the CP axis ratio performance is $L_r = 0.4\lambda_0$. When the sum of $L_r$ and $L_s$ is $\lambda_0$, the best CP axis ratio performance can be obtained. The ARBW of 14.6% can be achieved by the unit. Figure 6 shows the $S_{11}$ and AR curves of two coupling cavities. It is found by comparison that the performance of the spindle-shaped coupling cavity is preferable.

2 × 2 Array antenna design

**Feeding and coupling layer design**

The feeding design of the antenna adopts the same method as [17], and the structural parameters are shown in Table 1. If the distance between the antenna elements is less than one wavelength, the antenna sidelobe level will decrease [18]. Note that the distance between the feeding slots should accommodate four subarrays next to each other, while being compact enough to ensure proper spacing for the radiating slots to avoid a high grating lobes’ effect. The distance between the array elements is more than $\lambda_0$ if the spindle-shaped coupling cavity is directly excited by the feeding port.

The antenna adopts a combined structure of stepped design and tilted layer design as shown in Fig. 5. The size of the tilted waveguide is $T_1 \times T_2$ twisted by 45°, which decomposes the electric field into horizontal and vertical components. The electric field is further decomposed to obtain an orthogonal electric field.
with equal amplitude and 90° phase shift in the spindle-shaped cavity. A comparison with the former result is shown in Fig. 6. The AR is expanded to 17%.

**Table 1. Optimized parameters of the array antenna**

<table>
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<tr>
<th>Parameters</th>
<th>$W_1$</th>
<th>$W_2$</th>
<th>$W_{p1}$</th>
<th>$W_{p2}$</th>
<th>$S_1$</th>
<th>$S_2$</th>
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<td>5</td>
<td>13</td>
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<td>7</td>
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<td>$F_s$</td>
<td>$R_l$</td>
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<td>Values (mm)</td>
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<td>32</td>
<td>20</td>
<td>30</td>
<td>25</td>
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**Fig. 3.** Electric field distributions of the coupling slots at 5.8 GHz.

**Fig. 4.** Simulation of the $L_r$ and $L_s$: (a) AR for different values of $L_r$, and (b) AR for different values of $L_s$.

**Fig. 5.** Spindle-shaped cavity with tilted waveguide.

two parts constitute the antenna, including the feeding layer and the coupling layer. As shown in Fig. 1, four radiating elements in free space are positioned symmetrically in free space in the $x$- and $y$-directions. The distances between the coupling cavities are $F_i$.
and $S_1$. Figures 7 and 8 show the whole configuration of the multistep profile. The red dotted lines at the corners of the four cavities show the exact position of each radiating element relative to the groove in the center of the cavity. The overall structure is shown in Fig. 7. The stepped design and tilted design make the antenna more compact on the $y$-axis. The offset of the stepped layer is $S_2$. The feeding port and the stepped layer are connected.

Fig. 6. Simulated with different cavities: (a) $S_{11}$ and (b) AR.

Fig. 7. (a) Views of the feeding layer. (b) Views of the chamfering.

Fig. 8. Multi-stepped configuration of the antenna.

Fig. 9. Fabrication of the antenna.

Fig. 10. Simulated and measured results: (a) $S_{11}$ and (b) AR.
by chamfering to improve impedance matching, as shown in Fig. 7(b). The sidelobe level of the $E$ side is below $-12.65$ dB, and the minimum sidelobe level of the $H$ side can attain $-15.54$ dB.

Simulated and measured results

To verify the design, the 2 × 2 element antenna array was fabricated as shown in Fig. 9. The curve in Fig. 10 shows the measured and simulated $S_{11}$ and AR curves: the CP AR is below 3 dB at 5.41–6.02 GHz. Due to the mutual interference between the array elements, the ARBW of the CP array antenna is only 10.6%. As shown, the measurement and simulation results agree quite well with only a slight shift due to the fabrication tolerances. Each element of the antenna radiates evenly. Compared with a traditional waveguide slot array antenna, the beam of the antenna is always in the normal phase [19]. The simulated RHCP and left-hand circularly polarization patterns of 5.5, 5.7, and 5.9 GHz in the $E$- and $H$-planes are shown in Fig. 12. The radiation patterns of 5.5, 5.7, and 5.9 GHz in the $E$- and $H$-planes are shown in Fig. 11. The sidelobe levels of the antenna measured on the $E$-plane are $-12.7$, $-12.65$, and $-13.05$ dB, on the $H$-plane, the sidelobe levels are $-15.54$, 14.05, and $-13$ dB due to the large distance between the array elements. It can be seen from Fig. 12 that

![Simulated and measured radiation patterns in the E- and H-planes: (a) $E$-plane at 5.5 GHz, (b) $H$-plane at 5.5 GHz, (c) $E$-plane at 5.7 GHz, (d) $H$-plane at 5.7 GHz, (e) $E$-plane at 5.9 GHz, and (f) $H$-plane at 5.9 GHz.](image)

![Efficiency and gain of the array antenna.](image)

<table>
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<th>Ref.</th>
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<th>IBM (%)</th>
<th>Gain (dBi)</th>
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<tr>
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<td>10.6</td>
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<td>15.65</td>
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Table 2. Comparison with some previous works
the measured antenna-radiating efficiency is above 80% in the working bandwidth. The maximum antenna gain can attain 15.65 dB.

The asymmetric structure would increase the loss of the antenna, the insertion loss of each port is 6.08 dB at 5.8 GHz. Compared with the traditional waveguide slot antenna, the antenna has a wider ARBW. This antenna has lower loss compared to the substrate waveguide slot antenna. In [20], the length of the circular polarizer is $\lambda_0$, while the length of the cavity proposed in this paper is only $0.36\lambda_0$. Table 2 shows a comparison with the performances of the antennas in several literature studies.

**Conclusion**

In this paper, a circularly polarized $2 \times 2$ array antenna based on a spindel-shaped radiation cavity is proposed. The antenna has the advantages of high efficiency, wide ARBW, and low cost. The comparison of the three design methods demonstrates that adding the tilted waveguide can effectively improve the ARBW of the antenna to enhance the CP characteristics. Finally, the new CP antenna adopts the stepped design and the tilted design, which have wide IBW and ARBW as well as a good gain.

**References**


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