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RESEARCH ARTICLE

A novel wideband and circularly polarized cross-dipole antenna

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ABSTRACT

In this paper, we present a novel wideband circularly polarized (CP) composite, called cavity-backed crossed dipole antenna for 2.45 GHz industrial, scientific, and medical (ISM) band wireless communication. To excite the CP radiation effectively, a curved-delay line providing an orthogonal phase difference among the cross-dipole elements is attached at corners of the sequentially rotated elements. By choosing a proper radius of the curved-delay line, a wide input impedance of the antenna can be realized. Unlike conventional cross-dipole antennas, the proposed cross-dipole antenna is designed with an open stub added to the radiating arms of the dipole so that both impedance and axial ratio bandwidths are enhanced. The antenna is center-fed by a 50-Ω coaxial cable and is placed above a cavity-backed reflector to obtain a directional CP radiation pattern. With the advantage of being center-fed, a symmetric CP radiation pattern can be achieved across the entire operating bandwidth. To further improve the directivity and the radiation pattern, a rectangular cavity-backed reflector is used. Simulated and measured results confirm that the proposed antenna has good CP characteristics. The proposed antenna obtains a broad 3-dB axial ratio bandwidth of 49% (1.20 GHz, 1.96–3.16 GHz) and an impedance bandwidth of 67.7% (1.66 GHz, 1.69–3.35 GHz) for reflection coefficient (S_{11}) $\leqq -10$ dB. It also yields an average CP gain of 9.2 dBic across the operating bandwidth and a peak CP gain of 10 dBic. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS
circularly polarized; cross-dipole antenna; wideband antenna; impedance bandwidth; axial ratio (AR) bandwidth

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1. INTRODUCTION

Radio waves with circular polarization (CP) have attracted much attention for various modern wireless communication systems because they allow better transmission in adverse weather conditions, cancellation of multipath effects, and blackout in cases where the linearly polarized transmitter and receiver antennas are oriented perpendicular to each other [1,2]. What is more, general circularly polarized antenna bandwidth is very narrow, so it is difficult to meet the demands of the rapid development of wireless communication. Therefore, how to improve the impedance and axial ratio (AR) bandwidths for circularly polarized antenna is more important. There are many traditional methods to increase the bandwidth of CP antenna such as employing dual-fed structure [3], an auxiliary radiator [4], adding a wideband power divider in feeding network [5], and a serial feeding rotated structure [6].

Compared with the traditional methods mentioned in the preceding texts, one method using single dipole to improve the impedance and AR bandwidths of CP antennas is proposed because a dipole has several attractive features such as a simpler structure, lighter weight, and lower cost. The wideband CP dipole antenna with a 3-dB AR bandwidth of 27% presented in Ref. [7] is realized by increasing the width of the strip of the original strip dipole to excite CP operation. A broadband CP antenna in Ref. [8] is accomplished by combining strip dipoles with slots. However, these antennas have employed a single dipole to achieve circular polarization, which has several shortcomings such as large size and low gain.

Recently, the other method applying cross-dipole to enhance the AR bandwidth has attracted much attention [9–14]. The CP dipole presented in Ref. [9] uses a sequentially rotated configuration in itself, which is a simple cross-dipole CP antenna with a broad AR bandwidth of 15.6%. The antenna in Ref. [10] has a 3-dB AR bandwidth of 20% using the crossed bow-tie dipole instead of a crossed dipole for a broad AR bandwidth, but its structure is complex. The cross-dipole antenna in Ref. [11] goes through the use of meandering lines in the dipole arm to reduce size of radiation element, but its bandwidth is narrow and its back radiation is large. To add a cavity-backed for the cross dipoles [11,12], the back radiation can be suppressed; however, their bandwidths are still narrow. Although advanced cross dipoles in Refs [13] and [14] have reasonable 3-dB AR bandwidths of 27% and 28.6%, respectively, the back radiation for the antenna in Ref. [13] is larger and the size of the antenna in Ref. [14] is even larger.

In this paper, we propose a novel wideband circularly polarized cross-dipole antenna. Compared with the cross-dipole antennas in Refs [9–14], the proposed antenna is introduced with an open stub added to each dipole arm, so that both impedance and AR bandwidths are improved. In addition, the proposed antenna has a rectangular cavity-backed reflector which is placed at the bottom of the dipole so that both the unidirectional attern and the 3-dB AR beam width are improved. Its impedance bandwidth for reflection coefficient $(S_{11}) \leq -10$ dB is about 67.7% (1.69–3.35 GHz), and 3-dB AR bandwidth is about 52.6% (1.96–3.16 GHz)

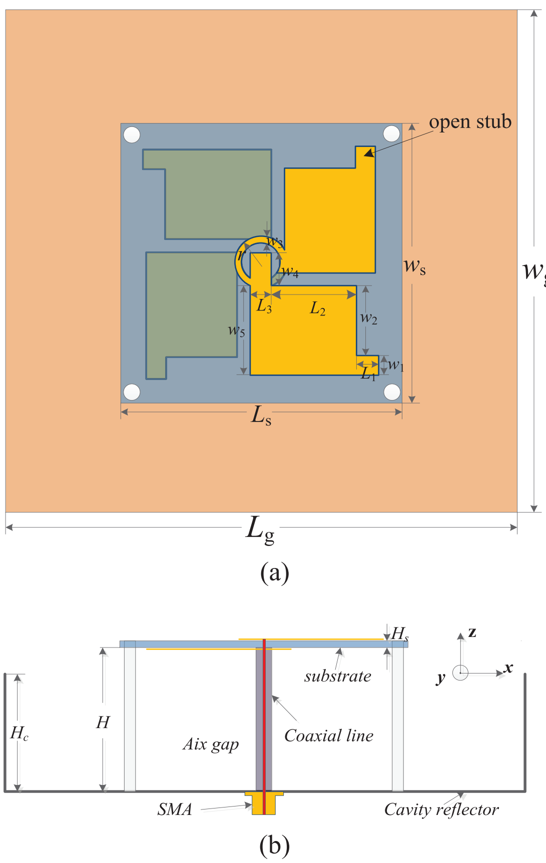

Figure 1. Geometry of the proposed antenna. (a) Top view and (b) side view of the antenna.

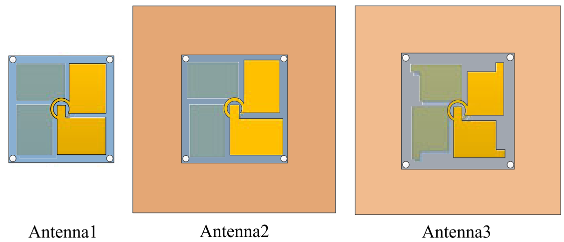

Figure 2. The process of antenna design.

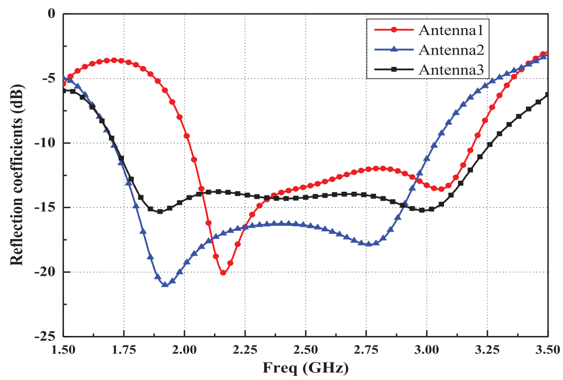

Figure 3. Reflection coefficients as a function of frequency for different cross dipoles.

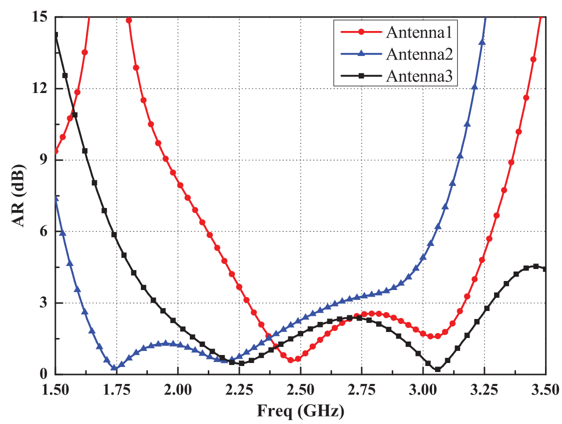

Figure 4. Axial ratio as a function of frequency for different crossed dipoles

around the center frequency of 2.45 GHz. The front-to-back ratio is 25 dB.

The remainder of the paper is organized as follows. Antenna geometry and performance are illustrated in Section II. The simulated and measured results are presented in Section III. Finally, in Section IV, we give the conclusion.

2. ANTENNA GEOMETRY AND PERFORMANCE

The geometry of the proposed CP cross-dipole antenna is shown in Figure 1. The main difference between the proposed printed cross-dipole antenna and that in Ref. [13] is that a rectangular cavity-backed reflector is

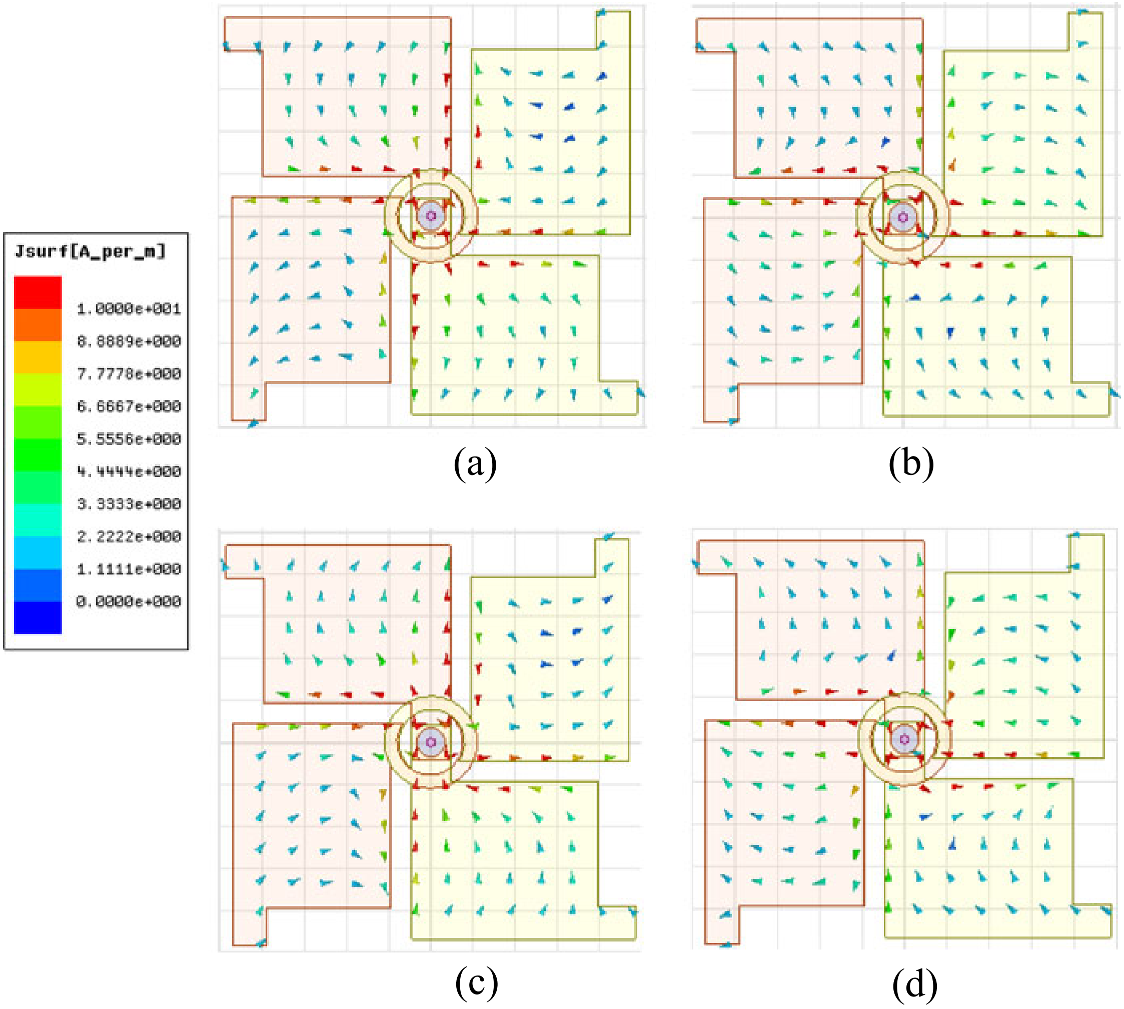

Figure 5. Simulated current distributions on the proposed antenna at 2.45 GHz for four phase angles: (a) 0°, (b) 90°, (c) 180°, and (d) 270°.

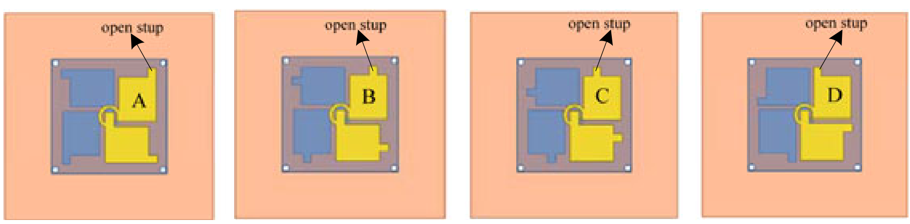

Figure 6. The different positions of the open stub.

appended. In addition, the dipole arms are also different from that in Ref. [13]. An open stub is added at the dipole arm. This stub contributes a characteristic impedance adjustment and results in a widely impedance and axial ratio bandwidths. The proposed antenna is fabricated on double layers of an $L_s \times w_s\,\mathrm{mm}^2$ FR4 substrate with a thickness of $H_s = 1.6\,\mathrm{mm}$, a relative permittivity of 4.4, and a loss tangent of 0.02. That is to say, the proposed antenna consists of two printed dipoles, a cavity-backed reflector, a semi-rigid coaxial cable, and four plastic pillars. Two dipole arms are printed on the upper side of the substrate, while the other arms are on the lower side. The cavity-backed reflector is a rectangular box with a dimension of $105 \times 105\,\mathrm{mm}^2$ and a height of $H_c = 24\,\mathrm{mm}$. The resonant frequency is determined by the value of $w_5 + L_2 + L_3$. To excite the CP radiation effectively, a curved-delay line providing an orthogonal phase difference among the cross-dipole elements is attached to the corners of the sequentially rotated elements. By choosing a proper radius of the curved-delay line, a wide input impedance of the antenna can be realized. In addition, compared with the exciting crossed dipole antenna, both the impedance and AR bandwidths of the proposed crossed dipole antenna are improved by the wide open end and the open stubs added to the open ends controlled by the value of w_1 and w_2. The antenna is center-fed by a 50-Ω coaxial cable and is placed above a cavity-backed reflector to obtain a directional CP radiation pattern. With the advantage of being center-fed, symmetric CP radiation patterns can be achieved across the entire operating bandwidth.

The back lobe of pattern becomes lower, and the front-to-back ratio is improved by employing the cavity-backed reflector at the bottom of the radiation patch. The proposed antenna is achieved by using the commercial EM software HFSS. The optimized antenna design parameters can meet the requirements of the maximal impedance and AR bandwidths. In Figure 1, $L_g = 105\,\mathrm{mm}$, $L_s = 58\,\mathrm{mm}$, $L_1 = 4.5\,\mathrm{mm}$, $L_2 = 17.5\,\mathrm{mm}$, $L_3 = 4.5\,\mathrm{mm}$, $w_g = 105\,\mathrm{mm}$, $w_s = 58\,\mathrm{mm}$, $w_1 = 4\,\mathrm{mm}$, $w_2 = 14.8\,\mathrm{mm}$, $w_3 = 1.6\,\mathrm{mm}$, $w_4 = 6.7\,\mathrm{mm}$, $w_5 = 18.5\,\mathrm{mm}$, and $r = 5.5\,\mathrm{mm}$.

Figure 2 illustrates the process of antenna design. The initial design (antenna 1) utilizes wide open ends, where the impedance and AR bandwidths of antenna 1 are 48.9% and 30.6%, respectively, but the front-to-back ratio is only 6 dB. To improve the back lobe of antenna pattern and the front-to-back ratio, a cavity-backed reflector is loaded to the bottom of the radiation patch (antenna 2) instead of the square reflector in antenna 1, where the impedance and AR bandwidths of antenna 2 are 55.1% and 42.4%, respectively. Finally, we add an open stub to the wide open end (antenna 3) so that a novel radiation mode in high frequency is excited. By adjusting the parameters slightly, both impedance and AR bandwidths are improved. The impedance and AR bandwidths of antenna 3 are 64.9% and 55.5%, respectively. The three structures mentioned in the preceding texts are simulated by using HFSS software, and reflection coefficients and AR are shown in Figures 3 and 4, respectively. Because adding an open stub can introduce a new resonance, the impedance and AR bandwidth can be increased by reasonably adjusting the size and location of open stub. Figures 3 and 4 illustrated that the impedance bandwidth broadened from 55.1 to 64.9% and the AR bandwidth broadened from 42.4 to 55.5%

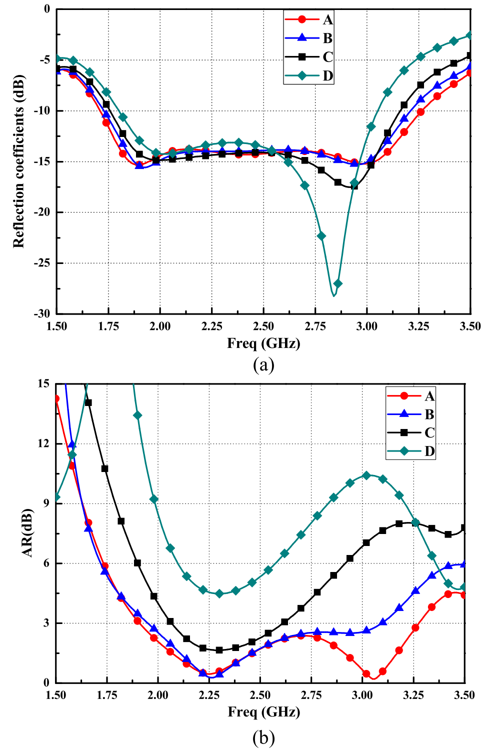

Figure 7. (a) Reflection coefficient and (b) axial ratio (AR) as a function of frequency for different positions of the open stub.

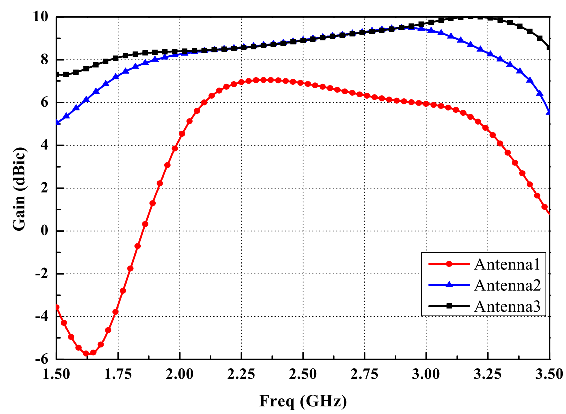

Figure 8. Gain as a function of frequency for different cross dipoles.

after adding the open stub. And the simulated current distributions on the surface of the proposed antenna at 2.45 GHz at different phases can be employed to explain the phenomenon, as shown in Figure 5. The proposed antenna employs an open stub loaded to the open ends to excite a novel radiation mode in high frequency so that the impedance and AR bandwidths can be expanded. Figures 6 and 7 illustrate the process of the determination for the optimum position of the open stub. Figure 7 shows that position A is the optimum position of the open stub. The gains of these three antennas are shown in Figure 8. From the simulations, we can see that the gains of antennas 2 and 3 are higher than that of antenna 1. Figure 9 shows radiation patterns of the different crossed dipoles at 2.45 GHz, where the back lobes of pattern for antennas 2 and 3 become lower than that of the pattern for antenna 1.

Additionally, the curved-delay line in antenna 3 provides a 90° phase difference so that the CP radiation can be generated. Moreover, this method of sequential-rotated excitation obtains a wide impedance bandwidth as well. The simulated reflection coefficient and AR of the antenna as a function of frequency for different width (w_2) and length (L_2) of the open ends are shown in Figures 10 and 11, respectively. Firstly, when all parameters except w_2 are constant, we can see that w_2 has significant influence both on reflection coefficient and AR, as shown in Figure 10. The reason is that the width

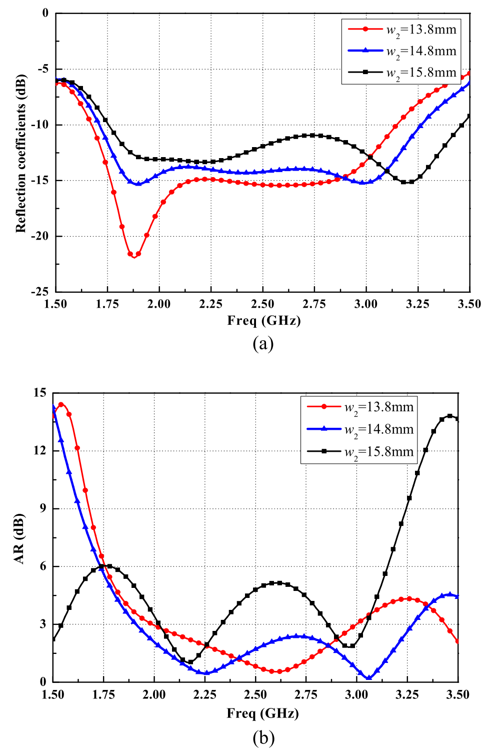

Figure 10. (a) Reflection coefficient and (b) AR as a function of frequency for different w_2.

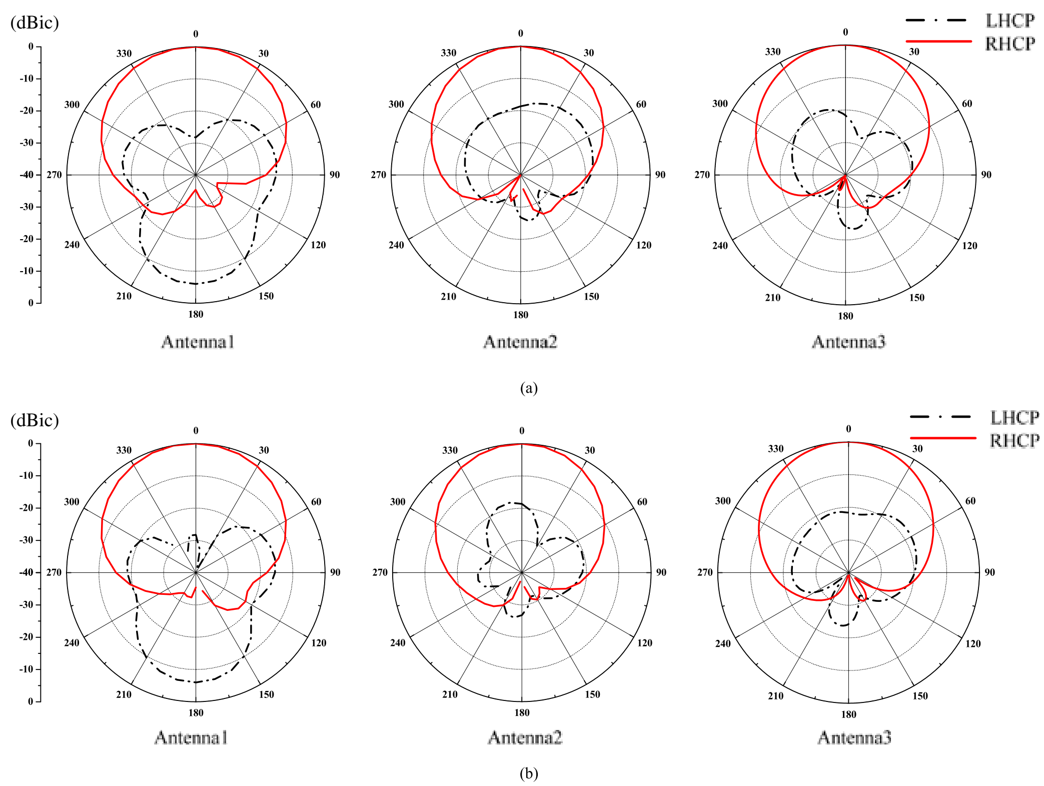

Figure 9. Radiation patterns of different cross dipoles at 2.45 GHz. (a) Phi = 0° (b) Phi = 90°.

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of the open ends affects not only the input impedance of the proposed antenna but also the phase difference between two orthogonal currents. When $w_2 = 14.8$ mm, the optimal results are obtained in terms of wide impedance and AR bandwidths.

Similarly, when all parameters except L_2 are constant, we can see that increasing the length (L_2) of the open ends causes the impedance bandwidth very slight change, as shown in Figure 11, but the AR bandwidth becomes larger. When $L_2 = 17.5$ mm, the optimal result is obtained. Figures 10–13 illustrate the simulated reflection coefficient and AR of the antenna as a function of frequency for different width (w_1) and length (L_1) of the open stubs, respectively. When w_1 changes from 3.5 to 4.5 mm in increments of 0.5 mm and the other parameters are constant, the impedance bandwidth has a little increase, but the AR bandwidth changes sharply. When $w_1 = 4$ mm, the optimal result is obtained. In Figure 13, L_1 has slight influence on reflection coefficient, but L_1 has a significant influence on AR in high frequency. When $L_1 = 4.5$ mm, the maximal AR bandwidth is obtained.

3. COMPARISON BETWEEN SIMULATED AND MEASURED RESULTS

A prototype of the proposed antenna is shown in Figure 14. The antenna has been fabricated on an FR4 printed circuit board with a copper thickness of 20 um via a standard etching technology. The cavity-backed reflector is constructed by using five aluminum plates (one 105×105 mm^2 and four 105×24 mm^2) with an aluminum thickness of 3 mm. The reflection coefficient is measured by using an Agilent N5230A vector network analyzer. AR and radiation patterns are evaluated in an anechoic chamber by using an NSI-800F10 antenna measurement system. Figure 15 shows the simulated and measured frequency responses of the proposed antenna. The measured reflection coefficient is in good agreement with the simulated value. The simulated and measured –10 dB impedance bandwidths are 1.59 GHz (1.70–3.29 GHz), which is 64.9% at the center frequency of 2.45 GHz, and 1.66 GHz (1.69–3.35 GHz), which is 67.7% at the center frequency of 2.45 GHz, respectively.

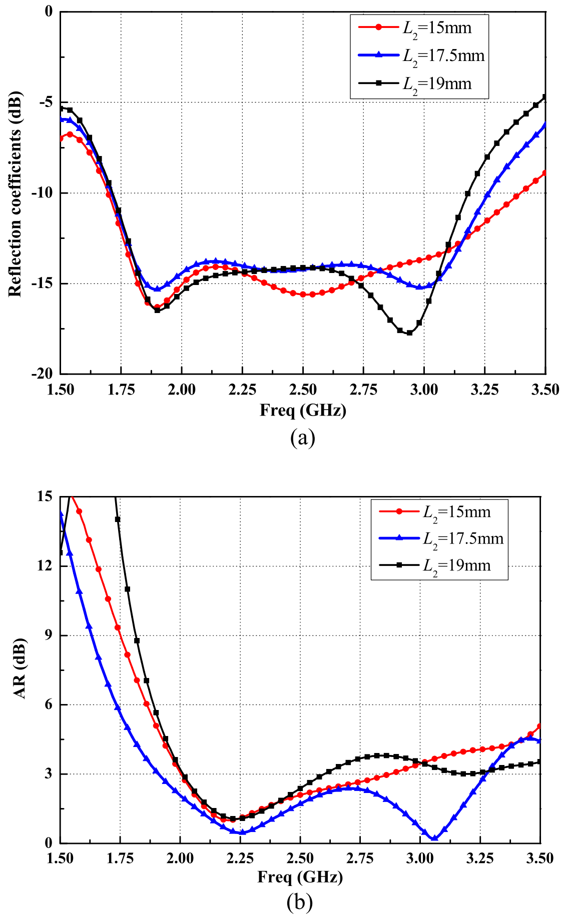

Figure 11. (a) Reflection coefficient and (b) AR as a function of frequency for different L_2.

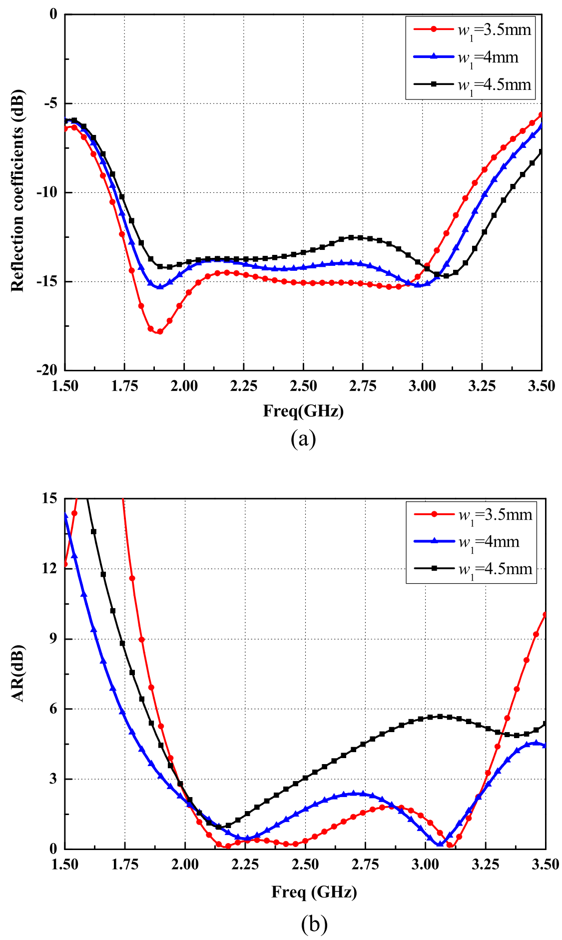

Figure 12. (a) Reflection coefficient and (b) AR as a function of frequency for different w_1.

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Figure 16 plots the simulated and measured ARs and right-hand circular polarization gains versus the frequency at 1.5–3.5 GHz for the proposed cross-dipole antenna. The measured 3-dB AR bandwidth is about 49%, from 1.96 to 3.16 GHz, and has a discrepancy of 3.6% with the HFSS simulated results (1.91–3.2 GHz). In Figure 16, the simulated and measured CP gains at the center frequency of 2.45 GHz are 10 and 9.7 dBic, respectively. As shown in Figure 17, the antenna yields stable and symmetric radiation pattern in Phi = 0°,

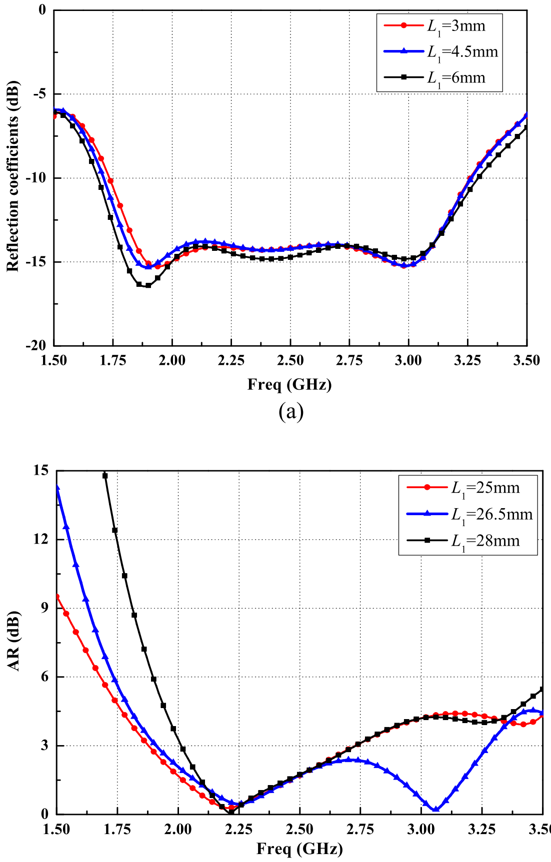

Figure 13. (a) Reflection coefficient and (b) AR as a function of frequency for different L_1.

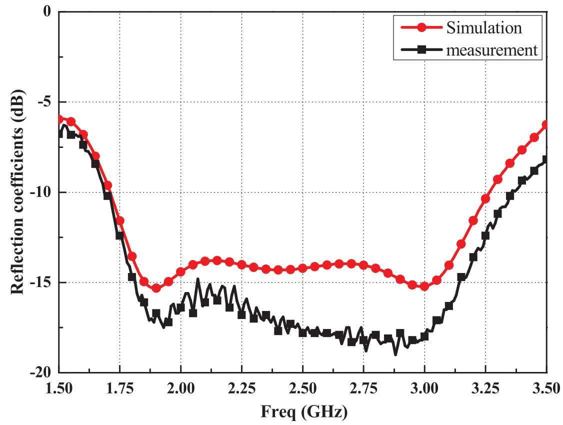

Figure 15. Measured and simulated reflection coefficient.

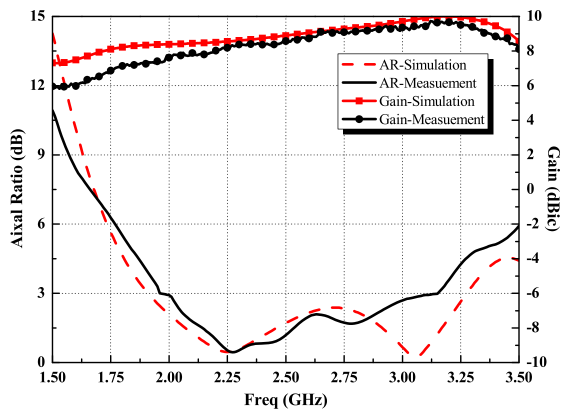

Figure 16. Measured and simulated AR and gain.

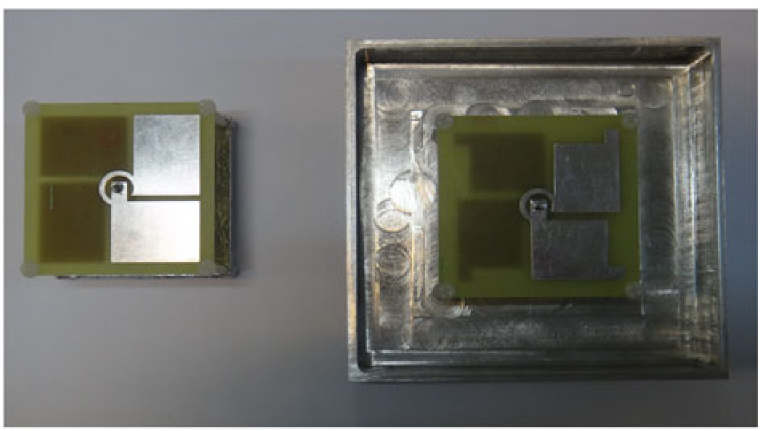

Figure 14. Photograph of the proposed antenna

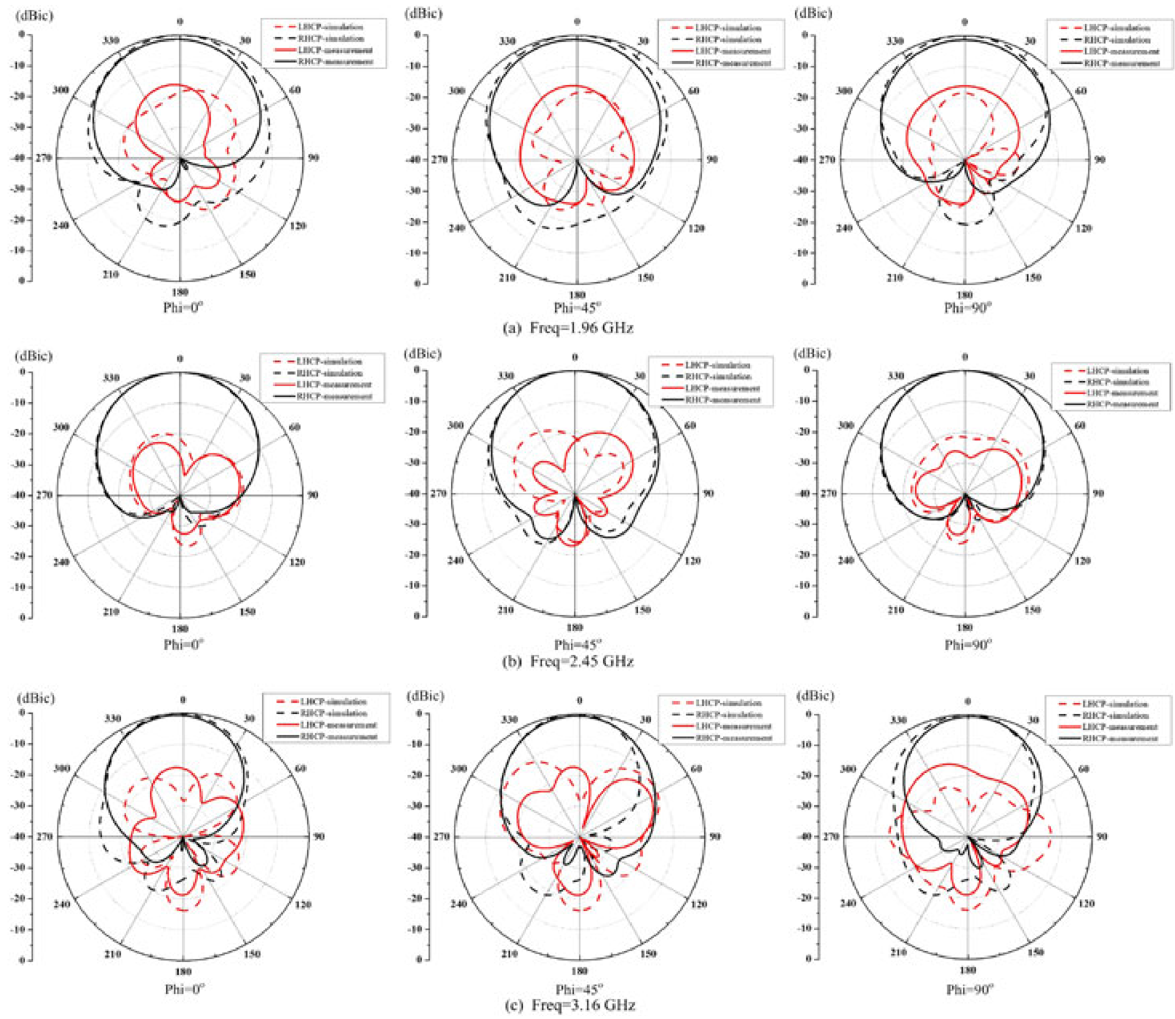

Figure 17. The measured and simulated radiation pattern of the antenna at different frequency: (a) 0°, (b) 45°, and (c) 90°.

Phi = 45°, and Phi = 90° planes at 1.96, 2.45, and 3.16 GHz. The 3-dB AR beam width is 88° for both Phi = 0° and Phi = 90° planes. Because a cavity-backed reflector is used in proposed CP antenna, its front-to-back ratio achieves 25 dB.

4. CONCLUSION

In this paper, a novel wideband CP composite called cavity-backed cross-dipole antenna has been proposed. The proposed antenna has a curved-delay line which can provide a wide-orthogonal phase difference among the cross-dipole elements, and adding an open stub to each open end can excite a radiation mode in the high frequency to enhance the bandwidths of impedance and AR. To reduce the back lobes of radiation pattern, a cavity-backed reflector was added under the main radiation patch. The proposed antenna has an impedance bandwidth of about 67.7% and a 3-dB AR bandwidth of about 49%. And it has an average CP gain of 9.2 dBic across the operating bandwidth and the maximum gain of 10 dBic at the broadside direction.

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