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Wide-Beamwidth Circularly Polarized Antenna and Its Application in a Sequential-Rotation Array with Enhanced Bandwidth

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Abstract—A wide-beamwidth circularly polarized (CP) asymmetric microstrip antenna is proposed by etching four novel unequal fan-shaped notches at the vertexes of the square radiator. A bandwidth of 1.5% and beamwidth of 156° are well achieved for an axial-ratio $\leq$ 3 dB (3-dB AR) at the central frequency of 1.575 GHz. To widen the bandwidth, the asymmetric microstrip antenna is further expanded with the construction of a 2×2 antenna array using sequentially rotated feeding technique. Moreover, by properly optimizing the distance between each two neighboring elements and the radii of the fan-shaped notches, the 3-dB AR bandwidth of the sequential-rotation array (SRA) is approximately extended to 7.8% with a wide-beamwidth at the central frequency of 1.6 GHz. In addition, the gain variation within the bandwidth is less than 1 dB. Finally, a laboratory model of the SRA has been fabricated, and acceptable agreement of the simulated and measured results makes it a good candidate for applications where wide-bandwidth, wide-beamwidth and small gain variation are needed.

1. INTRODUCTION

Due to the better immunity to polarization mismatch and multi-path distortion, circularly polarized (CP) antennas have been widely used in wireless communication systems. Up to now, various functions of CP antennas [1, 2] have been explored to suit different applications. Among these antennas, many techniques are developed for CP radiation, such as exciting two orthogonal patch modes and sequentially arranging several linearly polarized (LP) antenna elements. However, most of these designs focus on the improvement of operating bandwidth, half-power beamwidth (HPBW) or gain. Few works have been carried out to meet a radiation with wide 3-dB axial ratio (AR) angular beamwidth, which can improve the coverage area for effective data communication.

In recent years, several techniques have been proposed to widen the 3-dB AR beamwidth in [3–11], such as using the ground plane with small size, dielectric materials with high permittivity and metallic cavity. In [9], based on a patch antenna, a conducting wall and a ground with pyramidal structure were employed to obtain a 130° AR beamwidth at central frequency. However, this design made the antenna size bulky, which is not suitable for compact wireless devices. To achieve a wide AR beamwidth and low profile simultaneously, a CP antenna excited by four cross-slots underneath the ground plane was proposed in [10]. The antenna has a size of $0.94\lambda_0 \times 0.94\lambda_0 \times 0.2\lambda_0$ with a 3-dB AR beamwidth of 110° at 3.7 GHz. Recently, a low-profile CP antenna composed of two pairs of parallel dipoles was proposed with a 3-dB AR beamwidth of 126° in [11]. The antenna is $0.53\lambda_0 \times 0.53\lambda_0 \times 0.004\lambda_0$ at 1.6 GHz in size.

In this paper, a CP asymmetric microstrip antenna with a 3-dB AR beamwidth of 156° at the central frequency of 1.575 GHz is introduced. Four novel fan-shaped notches with different sizes at the vertexes of the square radiator contribute to the circular polarized property. The radiation pattern of the proposed antenna is mainly directed towards a half-space without a reflector or a metallic

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cavity. Due to its simple structure with single-fed and single-layered construction, the proposed CP asymmetric microstrip antenna can be easily employed as an array element. Furthermore, four asymmetric microstrip antennas are used to constitute a sequential-rotation array (SRA) [12–15], the 3-dB AR bandwidth of which is improved from 1.5% to 7.8% (1.524–1.648 GHz, which covers the GPS-band and CNSS-band) with the wide-beamwidth property. In addition, 1-dB the gain variation is achieved by properly optimizing the radii of the fan-shaped notches within the operating bandwidth. All these good performances make the SRA more favorable for applications where wide-bandwidth, wide-beamwidth and small gain variation are needed.

2. ASYMMETRIC MICROSTRIP ANTENNA

The configuration of the proposed asymmetric microstrip antenna is depicted in Fig. 1. The metal ground plane is placed on the bottom surface of the substrate, which is 70 mm × 70 mm × 3 mm ($0.373\lambda_0 \times 0.373\lambda_0 \times 0.016\lambda_0$) in size. The square radiator is located at the top surface of the substrate with a width of W_p. Four fan-shaped notches are positioned along the diagonal lines at the four vertexes [$(\pm W_p/2,\ \pm W_p/2)$], with different radii of r_1, r_2, r_3 and r_4, respectively. A coaxial feed is positioned along the $+Y$-axis with a distance of d_f from the center of the radiator. Optimized dimensions of the proposed asymmetric microstrip antenna are listed in Table 1.

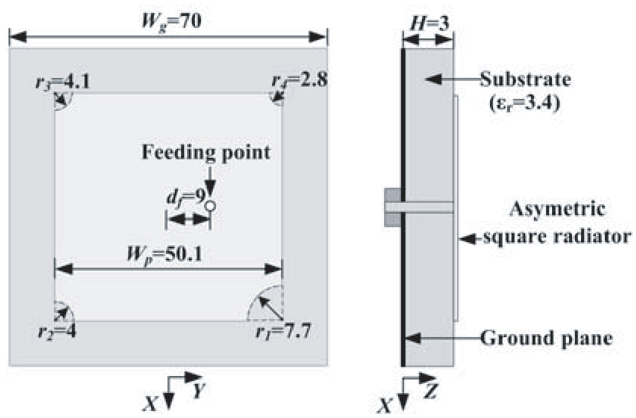
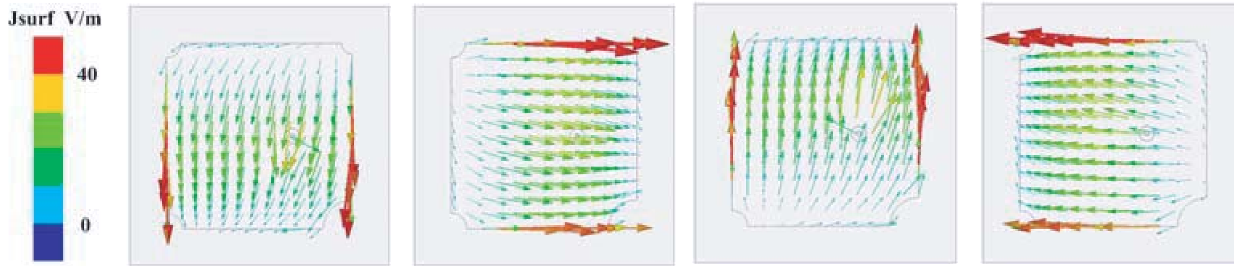


Figure 1. Geometry of the proposed antenna (unit: mm).

2.1. Operating Principle of CP Radiation

In this section, the operating principle of CP radiation is presented. A practical way of achieving CP is to trim the ends of two opposite corners of a square patch symmetrically and feed along centerline. By simply exchanging the trimmed-corners with four unequal fan-shaped notches at the four vertexes, the proposed asymmetric microstrip antenna not only generates a CP radiation, but also broadens the 3-dB AR beamwidth. The phenomenon relies on the four unequal fan-shaped notches with the idea of sequentially rotating perturbation [16]. The notches with the gradually smaller radii, approximately circling counterclockwise around the center, correspond to a right-handed circularly polarization (RHCP) pattern and weaken the cross-polarization (right-handed circularly polarization, LHCP) in a wide beamwidth. As a result, the 3-dB AR beamwidth of the proposed patch can be improved. In a similar way, LHCP can be achieved with the same feeding location when the radii of the notches are lessened clockwise. The slight difference is to well maintain the bandwidth of the antenna. Additionally, RHCP/LHCP is also obtained with the feeding point located along the Y-axis/X-axis.

Furthermore, to fully understand the operating principles, current distributions at the center frequency of 1.575 GHz on the square radiator in time domain are shown in Fig. 2. It can be clearly seen that the current distributions on the radiator are time-dependent anticlockwise rotating, indicating that the conditions for RHCP radiation are satisfied. Fig. 3 depicts the 3-dB AR beamwidth and gain



(a) (b) (c) (d)

Figure 2. Simulated current distribution on the radiator at 1.575 GHz with different phases. (a) 0°. (b) 90°. (c) 180°. (d) 270°.

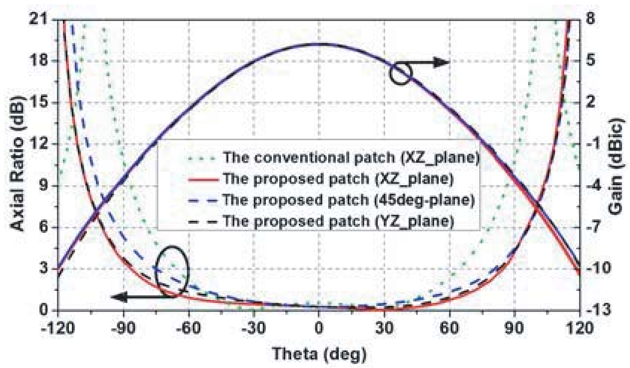


Figure 3. Simulated 3-dB axial ratios (ARs) and gain at 1.575 GHz.

of the conventional corner-truncated patch and the proposed asymmetric patch. In comparison, the proposed antenna can achieve a 3-dB AR beamwidth of 172° in the XZ-plane, which is 42° wider than the conventional patch. From the simulation results, 3-dB AR beamwidth is over 156° as the reference for all plane cuts, and the antenna gain can achieve at least -3.5 dBic. Based on the simulation results, the proposed antenna can have a good performance at low elevation angles for satellite reception.

2.2. Parametric Studies

In order to better comprehend the effect of the unequal fan-shaped notches etched on the square radiator, parametric studies are performed by varying the radii based on the optimized dimensions in this section. When one parameter is studied, the others are kept fixed as shown in Fig. 1.

To obtain RHCP and a wide 3-dB AR beamwidth, the design is guided by the rule that the radii of the notches should be lessened counterclockwise.

Firstly, the influence of r_1 on AR in the direction of the zenith is shown in Fig. 4(a). As r_1 is increased, the 3-dB AR operating frequency band is shifted upwards caused by the decreased physical dimension. The desired minimum AR is obtained with $r_1 = 7.7$ mm, and the AR becomes worse whether $r1$ increases or decreases. Because of slightly varying r_1 of 7.7 mm, two orthogonal resonant modes will not be maintained with equal magnitude and 90° phase shift, which is the necessary condition for a CP radiation.

Secondly, the effect of the varied r_2 on the AR is illustrated in Fig. 4(b) with fixed $r_1 = 7.7$ mm, $r_3 = 4.1$ mm and $r_4 = 2.8$ mm. The minimum AR can be obtained for $r_2 = 4.0$ mm at 1.575 GHz, and AR is deviated minimum value when r_2 diverges from 4.0 mm. Parameters r_3 and r_4 impose their influences on AR in the same manner with r_2, as shown in Figs. 4(c)–(d).

Lastly, the optimal AR is acquired with the radii of $r_1 = 7.7$ mm, $r_2 = 4.0$ mm, $r_3 = 4.1$ mm and $r_4 = 2.8$ mm. Here, the 3-dB AR beamwidth of the patch is not affected by the slightly lager radius

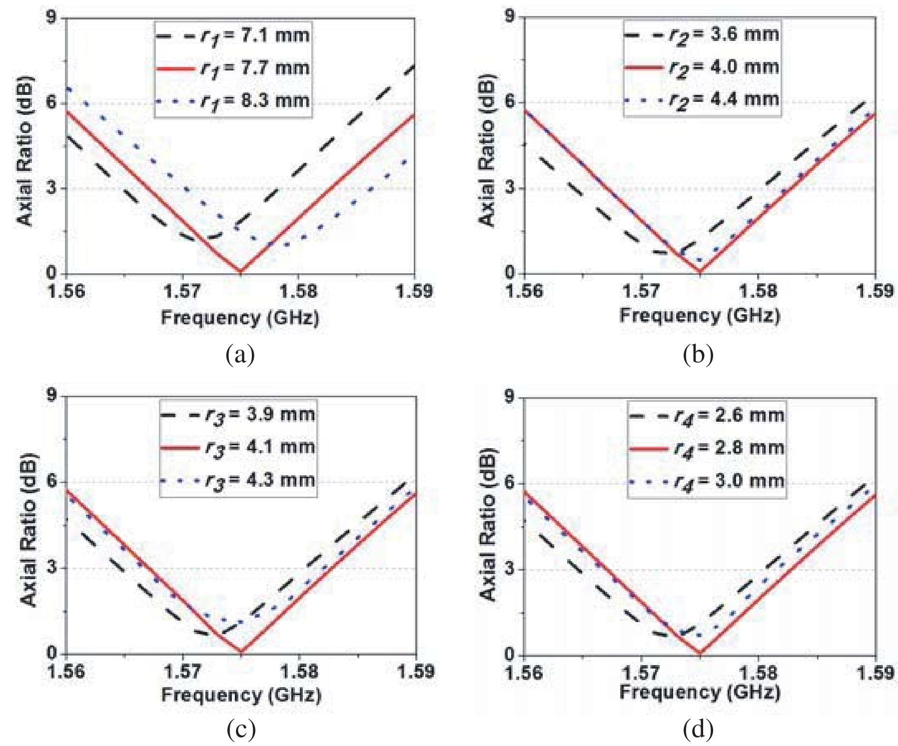


Figure 4. Simulated axial ratios (ARs) in the direction of the zenith with variations of (a) r_1, (b) r_2, (c) r_3, (d) r_4.

r_3. In brief, by controlling the radii of the unequal circular notches, two orthogonal modes with equal magnitude and 90° phase shift are able to be achieved for CP radiation.

3. CP SEQUENTIAL-ROTATION ARRAY

With the development of personal communication service, the requirement for wideband has increased significantly. Therefore, the application of the proposed asymmetric microstrip antenna is limited due to the narrow bandwidth. Herein, a sequential-rotation array (SRA) is employed for its considerable AR and impedance bandwidth enhancing capability [12, 13].

The CP SRA is composed of four identical asymmetric microstrip antenna elements, which are rotated around a center point in Fig. 5. By using a 1-to-4 probe-to-microstrip feeding network [11], the phases of these elements are set to be 0°, 90°, 180° and 270°, respectively. The RHCP can be achieved when the phases increase gradually along the anticlockwise direction. Fig. 6(a) shows that the magnitude difference between the feeding ports, namely $p2$ to $p5$, is less than 0.5 dB. It is also observed that the phase difference between the adjacent ports is attained from 75° to 102° in Fig. 6(b). The simulated results of the S parameters show that the designated feeding network meets the requirement of the CP SRA well.

The main step of design is to optimize the distance between two neighboring elements due to its great influence on the 3-dB AR beamwidth. For a wide 3-dB AR beamwidth of the CP SRA, the AR in the XZ-plane is simulated under varied distance d as shown in Fig. 7. When $d = 0.3\lambda_0$ (λ_0 is wavelength in the free space at central frequency $f_0 = 1.6$ GHz), the 3-dB AR beamwidth is approximately 83° and 78° when $d = 0.6\lambda_0$. At $d = 0.45\lambda_0$, the 3-dB AR beamwidth can cover a wide range in the polar axis of $-90°$ to $+93°$ at 1.6 GHz. Beyond $0.45\lambda_0$, the 3-dB AR beamwidth is gradually narrowed. Hence, the valid distance d of the proposed SRA is around $0.45\lambda_0$.

In addition, the gain bandwidth constraint of SRA has been a severe issue on thin substrates, because the gain variation is lager in the enhanced AR bandwidth [14, 15]. To get a minimum gain

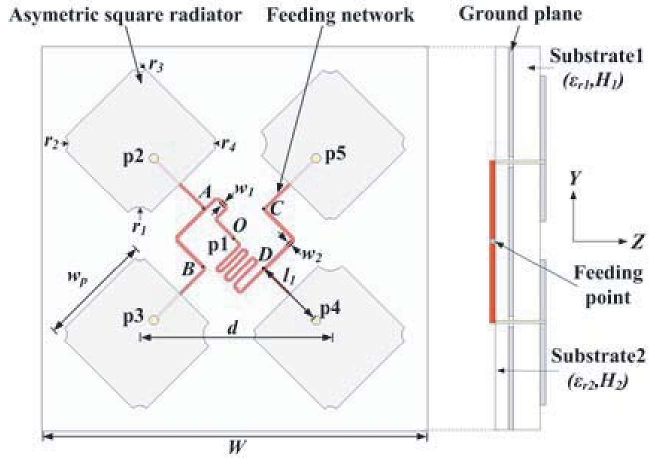
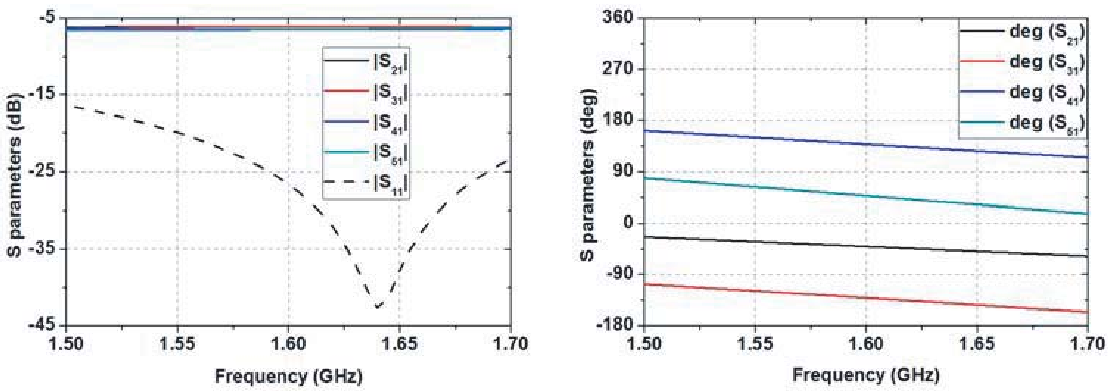


Figure 5. Overall configuration of the proposed CP SRA.



(a) (b)

Figure 6. Simulated S parameters of the feeding network. (a) Magnitude (dB). (b) Phase (deg).

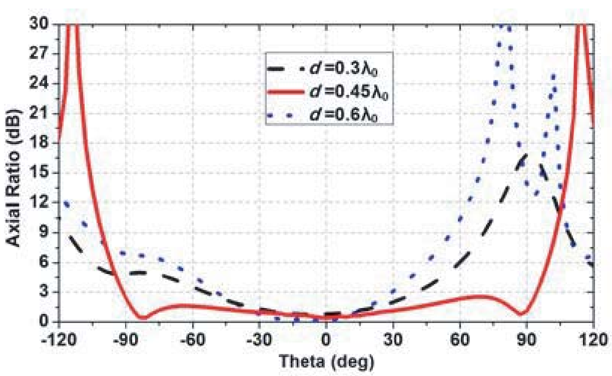


Figure 7. AR with variation of d in the XZ-plane at 1.6 GHz.

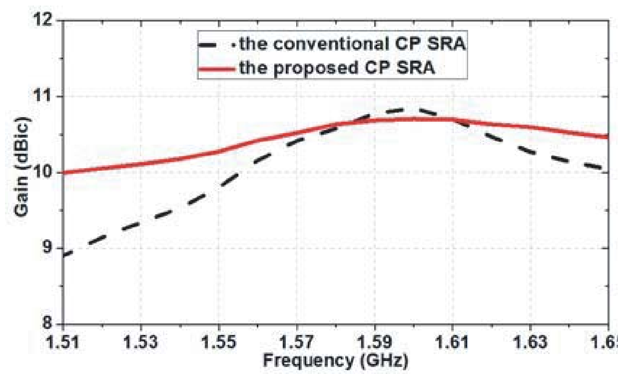


Figure 8. Gain-frequency properties for different types of SRAs.

variation within the enhanced AR bandwidth, the radii of the unequal fan-shaped notches on the element are optimized. The gain-frequency properties for two types of SRAs are depicted in Fig. 8. As shown, the 1-dB gain bandwidth of the proposed CP SRA is 30% wider than the conventional CP SRA whose element size is the same as the asymmetric microstrip antenna proposed in Section 2. It is because the changes in the radii of the unequal fan-shaped notches make the element obtain an elliptical polarization, which makes the gain bandwidth much wider than the conventional SRA with CP element. The detailed analysis of the previously mentioned conclusion has been minutely carried out in [12].

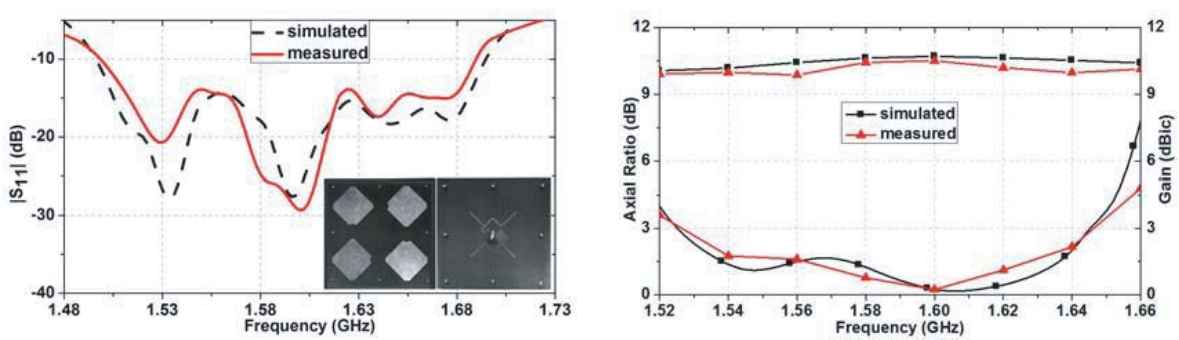
After completing the design of the proposed SRA shown in Fig. 5, all of its dimensional parameters are determined and tabulated in Table 1.

Table 1. List of all the dimensional parameters for the asymmetric microstrip antenna in Fig. 5 and Fig. 8.

Parameters	d	w_p	r_1	r_2	r_3	r_4
Values	84 mm	50.1 mm	9.5 mm	4.2 mm	3.8 mm	2.8 mm
Parameters	ε_{r1}	H_1	ε_{r2}	H_2	w_1	w_2
Values	3.4	3 mm	2.65	0.6 mm	1.2 mm	1.5 mm
Parameters	l_1	OA	AB	OC	CD	W
Values	30 mm	32 mm	32 mm	96 mm	32 mm	170 mm

4. RESULTS

In this section, the overall layout of the designed CP SRA in Fig. 5 is simulated using the ANSYS HFSS and fabricated to verify the predicted results.



(a) (b)

Figure 9. Simulated and measured antenna parameters as a function of frequency. (a) $|S_{11}|$; (b) Peak RHCP radiation gain and axial ratios (AR).

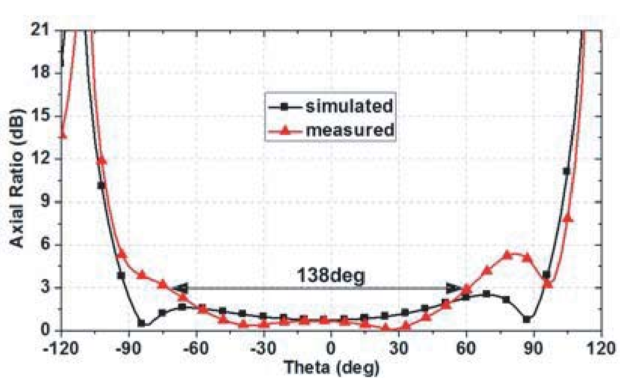


Figure 10. Simulated and measured 3-dB axial ratio in the XZ-plane at 1.6 GHz.

The measured results of $|S_{11}|$, peak RHCP radiation gain and AR as a function of frequency are compared with the simulated ones in Figs. 9(a) and (b). In the desired band of 1.524–1.648 GHz, we have well achieved the measured results of AR < 3 dB, $|S_{11}| < -10$ dB and Gain > 10 dBic, which agree well with the simulations. The measured gain variation is less than 1 dB. Fig. 10 depicts the simulated and measured ARs in the XZ-plane at the central frequency 1.6 GHz. The measured 3-dB AR beamwidth reaches 138°, i.e., −74° to 64°. Fig. 11 shows the simulated and measured radiation patterns at 1.6 GHz. It is noted that the cross-polarization level is less than −27 dB.

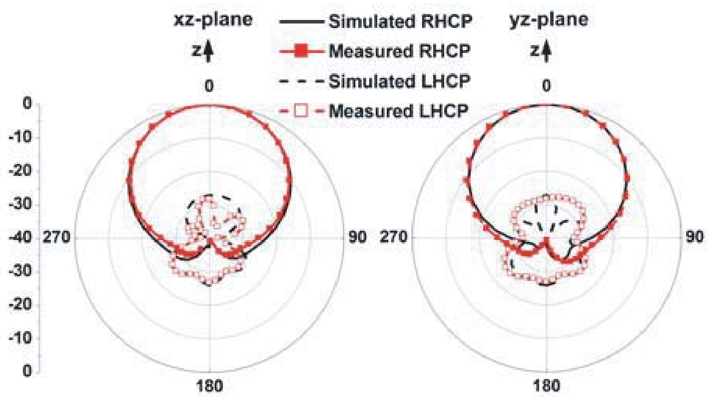


Figure 11. Simulated and measured radiation patterns at 1.6 GHz.

5. CONCLUSION

In this paper, a wide-beamwidth circularly polarized (CP) asymmetric microstrip antenna is proposed. Four unequal fan-shaped notches are etched at the vertexes of the square radiator, which make its radiation pattern cover a wide angular range with the beamwidth of about 156°. The proposed asymmetric microstrip has a 3-dB axial ratio (AR) bandwidth of 1.5%. For wider bandwidth, a circularly polarized sequential-rotation array (SRA) has been proposed, designed and tested. By employing the sequential-rotation feeding network and optimizing the radii of the fan-shaped notches, the 3-dB AR bandwidth is expanded from 1.5% to 7.8% with a good 1-dB gain variation. As shown in both simulation and measurement, a wide-beamwidth of 138° is also obtained at the central frequency of 1.6 GHz. Therefore, the proposed SRA can be applied in systems where wide AR bandwidth, wide-beamwidth and small gain variation are needed.

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