A Wideband Sequential-Phase Fed Circularly Polarized Patch Array

Changjiang Deng, Yue Li, Zhijun Zhang, and Zhenghe Feng

***Abstract*—This communication presents a wideband circularly polarized (CP) 2 × 2 patch array using a sequential-phase feeding network. By combining three operating modes, both axial ratio (AR) and impedance bandwidths are enhanced and wider than those of previous published sequential-fed single-layer patch arrays. These three CP operating modes are tuned and matched by optimizing the truncated corners of patch elements and the sequential-phase feeding network. A prototype of the proposed patch array is built to validate the design experimentally. The measured −10-dB impedance bandwidth is 1.03 GHz (5.20–6.23 GHz), and the measured 3-dB AR bandwidth is 0.7 GHz (5.25–5.95 GHz), or 12.7% corresponding to the center frequency of 5.5 GHz. The measured peak gain is about 12 dBic and the gain variation is less than 3 dB within the AR bandwidth.**

***Index Terms*—Broadband antenna, circular polarization, microstrip array, sequential rotation.**

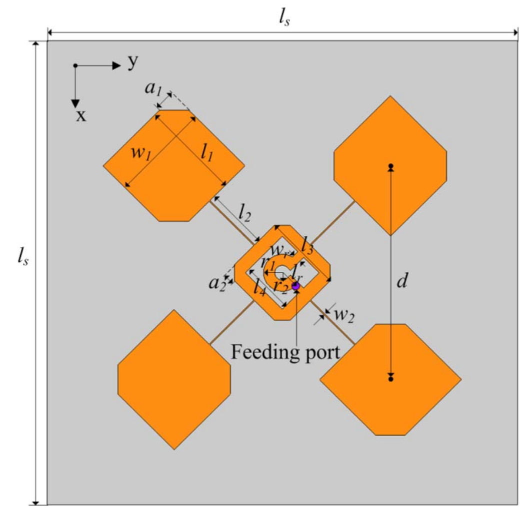

Fig. 1. Geometry and dimensions of the proposed 2 × 2 array.

I. Introduction

Sequential rotation (SR) technique has been extensively used to improve impedance and AR performances in 2 × 2 array design. The mechanism of SR technique is analyzed theoretically and experimentally in [1], and some useful design principles have also been summarized. It is proved in [2] that the circularly polarized (CP) bandwidth in the axial broadside direction is frequency independent as far as one would keep the perfect magnitude and phase to the four elements. However, owing to magnitude errors, phase errors, impedance mismatch and mutual coupling, the practical CP bandwidth is limited by the feeding network and/or the radiating elements.

The feeding network is usually wideband and various structures have been proposed in [3]–[12]. Proximity-coupled [3]–[8], aperture-coupled [9], [10], edge-fed, coaxial-fed [11], and CPW-fed [12] methods are the typical ways for designing sequential-phase feeding networks with phases of 0°, 90°, 180°, and 270° at four ports. However, these proposed 2 × 2 patch arrays have at least two substrate layers, which are not suitable for monolithic integration. Some improvements have been made to reduce substrate layers by utilizing CPW-fed or edge-fed methods [13]–[15]. However, the single-layer 2 × 2 patch arrays have a narrow CP bandwidth (less than 6%), which are not suitable for wideband applications.

The radiating elements can be wideband, such as DRA [16]–[18], or narrowband, such as patch. For 2 × 2 patch array design, the CP bandwidth is mainly limited by the nature of patch elements. Combining several patch element's modes together is a novel way to broaden array's bandwidth. Cutting corners on patch elements not only enhances patch's AR performance, but also separates the two orthogonal modes in the diagonals, which helps increase the array's bandwidth. However, the objective of cutting corners in [3]–[15] is to get the optimized AR of the patch elements, which is not large enough to separates the two orthogonal modes. It is proved in [19] that SR technique is insensitive to the polarization of patch elements. Thus, the truncated corners can be further increased and the polarization of patch elements changes from linearly polarized (LP) to CP to LP in a relatively wide frequency band.

In [20], a shorted loop is adopted to provide stable phase difference and the corners of patch elements are truncated large. The loop mode and the patch element's CP mode are combined, and a CP bandwidth of about 7% is achieved. Actually, the loop mode can also be viewed as the patch element's LP mode. In this communication, the loop-fed structure in [20] is modified and excited by a probe to reduce substrate layer. Besides, the LP-CP-LP mode of patch elements in 2 × 2 patch array is analyzed comprehensively for the first time. By exciting the three modes with sequential phases, a broad AR bandwidth of more than 12% can be achieved, which is a great enhancement when compared with other published single-layer 2 × 2 patch arrays.

II. Antenna Design

Fig. 1 shows the basic geometry of the proposed 2 × 2 patch array. The central part is the feeding network, which consists of a loop and a sector of 270°. The loop, which is 45° tilted from the x-axis, is formed by cutting an $l_4 \times l_4$-sized square from an $l_3 \times l_3$-sized square. Four triangles are truncated from the corners of the loop. The outer radius and the inner radius of the sector are r_1 and r_2, respectively. The loop and the sector are connected via two strips of equal length. The feeding port is placed on one of the strips and has a distance of l_r from the center point. Four corner-truncated square patches are arranged in a sequentially rotated structure and are connected to the feeding network via four strips. The proposed antenna is printed on a single-layer Teflon substrate with $\varepsilon_r = 2.5, \tan\delta = 0.002$, and thickness $h = 1.5$ mm. The dimensions of the array are optimized by using Ansoft HFSS full-

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TABLE I
DETAILED DIMENSIONS (UNIT: mm)

l_s	l_1	w_1	l_2	w_2	l_3	l_4
75	16	16	10.1	0.2	12.6	8.3
d	l_r	w_r	a_1	a_2	r_1	r_2
34.5	3	1.3	3.3	1.8	3	1.2

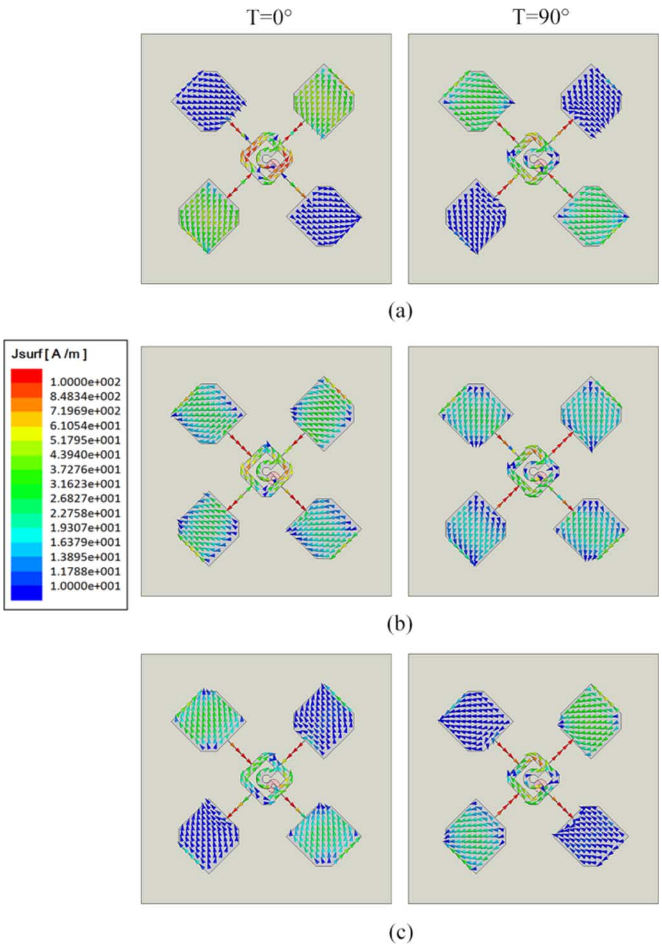

Fig. 2. Current distribution on the proposed array at different frequency: (a) 5.3 GHz, (b) 5.68 GHz, (c) 5.9 GHz.

wave simulator and the detailed values of each parameter are listed in Table I.

The center frequency of the proposed array is designed at 5.5 GHz and the effective wavelength is 41.2 mm, according to the equation $\lambda_g = 2\lambda_0/(1+\varepsilon_r)$. The sector of 270° has a mean arc length of about $\lambda_g/4$, which not only serves as an impedance transformer but also provides a phase difference of 90°. By connecting the sector and the loop via two strips, the loop's one-wavelength mode is excited and sequential phases of 0°, 90°, 180°, and 270° appear at the loop's four arms. The loop is extended by four $\lambda_g/4$ strips, which are used to provide stable input impedance for the four arms of the loop. Taking the center frequency for example, the edge impedance of the patch elements is about $120 + \mathrm{j}30\ \Omega$, the characteristic impedance of the transformers is about 180 Ω. Thus, the input impedance via the $\lambda_g/4$ transformer is about 250-j60 Ω. Then, the four input impedances via the loop are transformed into about $40 - \mathrm{j}2\ \Omega$, which is well matched to 50 Ω.

In this communication, two LP modes and one CP mode of the patch elements are excited at different frequencies by truncating large corners. Fig. 2 shows the current distribution on the array at different frequencies with different phases. In the low frequency, the resonance is mainly determined by the longer diagonal of the patch elements. In Fig. 2(a), it can be observed that a pair of elements on the diagonal of the array is excited at $\mathrm{T} = 0°$, and the other pair of elements is excited at $\mathrm{T} = 90°$. Moreover, the current directions in $\mathrm{T} = 0°$ and 90° are orthogonal. Thus, the array is CP even though the elements are LP. A similar phenomenon is found in Fig. 2(c), where the resonance in the high frequency is determined by the shorter diagonal of the patch elements. In Fig. 2(b), it is shown that all the four elements are excited at the same time with consistent current directions at $\mathrm{T} = 0°$, and the current directions rotate 90° at $\mathrm{T} = 90°$. Thus, both the array and the elements are CP in the middle frequency. By combining the three CP operating modes at different frequencies, right-hand circular polarization (RHCP) is achieved in a broad bandwidth.

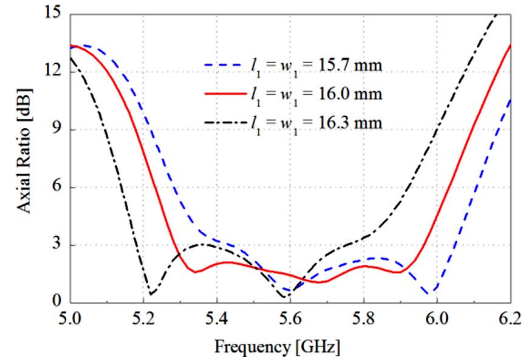

Fig. 3. Simulated AR of the proposed array with different element size.

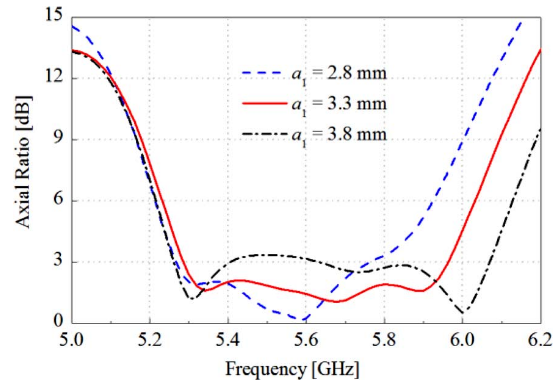

Fig. 4. Simulated AR of the proposed array with different a_1.

A parameter study is carried out to further verify the operating principle mentioned above. Fig. 3 shows the effect of elements' size on the AR performance of the array, which affects both the longer and shorter diagonals of elements. It can be observed that the AR curve moves downward with the increase of elements' size. Fig. 4 shows the effect of a_1 on AR, which only affects the shorter diagonal of elements. It is shown that as a_1 increases, the resonance in the high frequency shifts upward, while the resonance in the low frequency changes slightly. These results verify that the resonances in the low and high frequencies are determined by the longer and shorter diagonals of elements, respectively.

III. EXPERIMENTAL RESULTS

Fig. 5 shows the prototype of the proposed 2×2 patch array. The measured reflection coefficient of the array is shown in Fig. 6, which agrees well with the simulated result. The measured -10-dB reflection coefficient bandwidth is from 5.2 GHz to 6.23 GHz, or about

TABLE II
A COMPARISON TABLE BETWEEN THE PROPOSED 2 × 2 ARRAY AND OTHER SINGLE-LAYER 2 × 2 ARRAYS

2×2 arrays	[13]	[14]	[15]	[20]	Proposed
10-dB impedance bandwidth (%)	7.3	15.45	8	6	>19
3-dB AR bandwidth (%)	4.4	5.4	4.8	6.8	12.7
Total size (λ_g)	Not Given	1.96×1.96×0.031	1.92×1.92×0.021	2.17×2.17×0.076	1.82×1.82×0.036

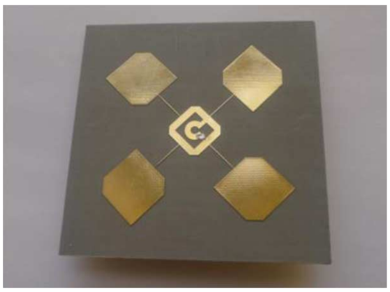

Fig. 5. Photograph of the fabricated 2 × 2 patch array.

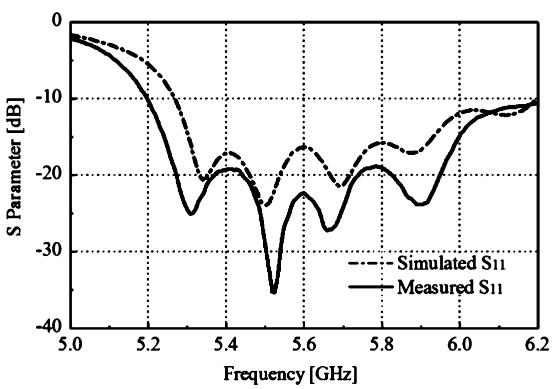

Fig. 6. Simulated and measured reflection coefficient of the 2 × 2 array.

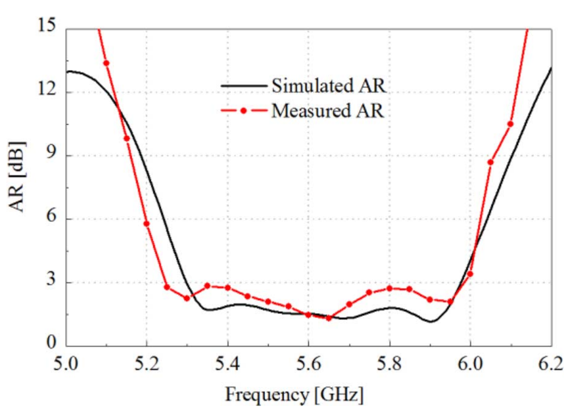

Fig. 7. Simulated and measured axial ratio of the 2 × 2 array.

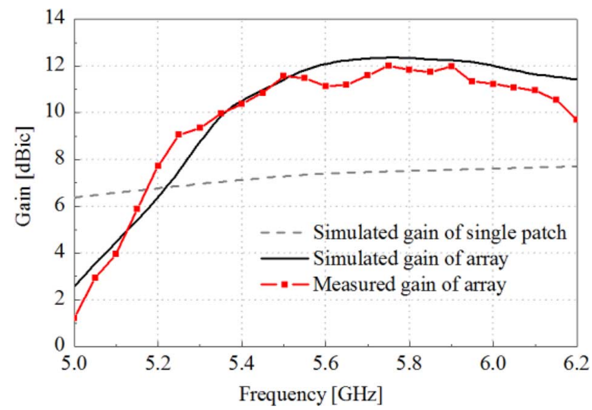

Fig. 8. Simulated and measured gains.

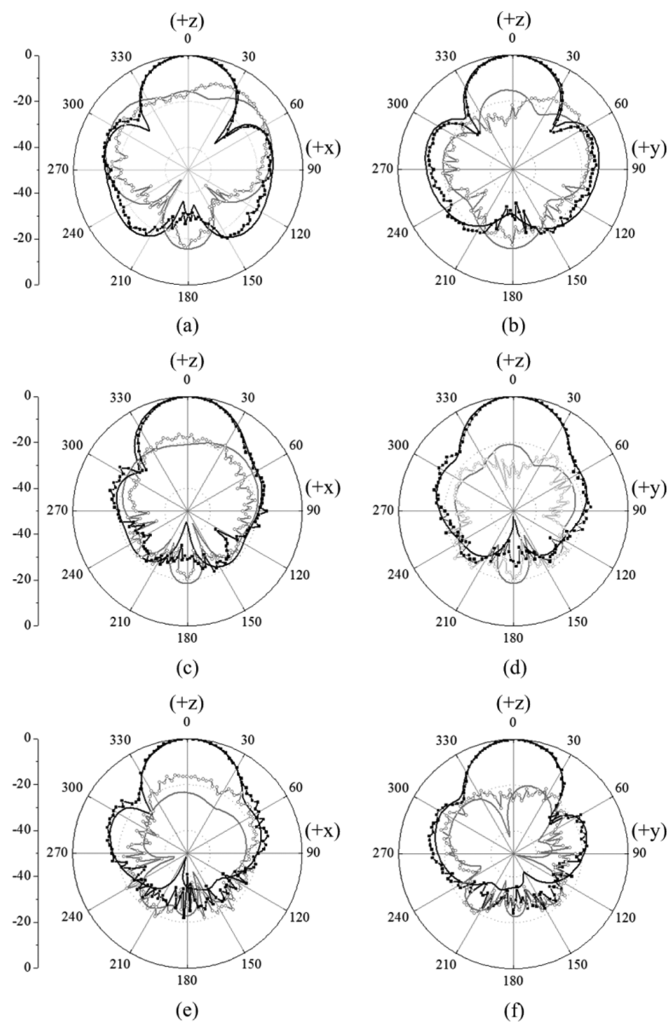

Fig. 9. Simulated and measured normalized radiation patterns of the 2 × 2 array. (a),(b) 5.3 GHz; (c),(d) 5.6 GHz; (e),(f) 5.9 GHz.

18.7% corresponding to the center frequency of 5.5 GHz. The fact that the measured results have smaller values than the simulated results is mainly attributed to dielectric loss and fabrication error. Fig. 7 shows the simulated and measured AR results. The measured 3-dB AR bandwidth of the array is from 5.25 GHz to 5.95 GHz, or about 12.7%, which is within the −10-dB reflection coefficient bandwidth. It can also be observed that the measured ARs below 3 dB vary a little larger than the simulated ones, and a wider AR bandwidth is achieved. This difference between simulation and measurement is caused by fabrication error and measurement error, also with uncertain permittivity of substrate.

Fig. 8 shows the simulated and measured gains. It is shown that the measured gain of the array is about 11.5-dBic in most of the 3-dB AR bandwidth, which is about 4.5-dB higher than that of a single element. It is also observed that the gain in the low frequency drops fast with the decrease of frequency. This is mainly caused by the limited bandwidth of the feeding network. The measured gain variation is less than 3 dB in the concerned 3 AR bandwidth and the measured peak gain is about 12 dBic at 5.75 GHz.

The simulated and measured normalized radiation patterns in the xz- and yz-planes at different frequencies are shown in Fig. 9. It is shown that the measured results agree well with the simulated results. The measured front-to-back ratio is better than 16 dB at 5.3 GHz, better than 20 dB at 5.6 GHz and 5.9 GHz. Also, the co-polarization (RHCP) gain at broadside is 17 dB higher than the cross-polarization (left-hand circular polarization, LHCP) gain at all the frequencies in both planes.

The comparison of the proposed patch array with other referenced single-layer 2 × 2 arrays is listed in Table II. It is shown that the comprehensive bandwidth of the proposed array with $\mathrm{S}_{11} < -10$ dB, $\mathrm{AR} < 3$ dB, is double enhanced, when compared with other referenced single-layer 2 × 2 patch arrays. Besides, the planar size of the proposed array is smallest among all the designs.

IV. Conclusion

A compact single-layer wideband CP 2 × 2 patch array is proposed in this communication. Three operating modes of patch elements at different frequencies are analyzed and excited by using a sequential-phase feeding network. Both impedance and AR bandwidths are greatly enhanced by combining these three modes together, which can be tuned and matched by optimizing the truncated corners of elements and the sequential-phase feeding network. The measured bandwidth with $\mathrm{S}_{11} < -10$ dB, $\mathrm{AR} < 3$ dB is 700 MHz, or 12.7% corresponding to the center frequency, which is double wider than the previous published single-layer 2 × 2 patch arrays. The measured peak gain is 12 dBic. In the band of 5.45–5.9 GHz, the gain is about 11.5 dBic, and the gain variation is less than 3 dB within the 3-dB AR bandwidth. The proposed 2 × 2 patch array, with the advantages of single-layer structure, and wide AR bandwidth, is a promising candidate for CP array design.

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