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RESEARCH ARTICLE

Circularly polarized 2 × 2 microstrip antenna array for application as a reflectarray feed

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Abstract
This article describes a circularly polarized 2 × 2 microstrip antenna array with corporate feeding to be used at K-Band (18.7-19.2 GHz) as a reflectarray feed. A design approach is proposed for the improvement of axial ratio and impedance bandwidths of circularly polarized microstrip antenna arrays with sequential rotation. A parametric analysis is also proposed to evaluate accurately the array phase center position. An array prototype has been designed, fabricated, and tested. The good agreement obtained between simulation and experimental results provides validation of the design approach and proof of the proposed concept.

KEYWORDS
circular polarization, feed network, microstrip antenna arrays, phase center, reflectarrays

1 | INTRODUCTION

The polarization performance of circularly polarized reflectarrays depends critically on the polarization purity of the feed.[1] Due to well-known advantages, such as, small size, light weight, compactness, and low cost, microstrip arrays can be used in satellite-based communication systems as reflectarray feeds. However, they are also known to exhibit narrow axial ratio and impedance bandwidths. The sequential rotation technique[2–4] can be used to surpass these disadvantages, which has been implemented by using corporate or series-feeding networks.[5–8] In all these contributions, the main goal was to achieve circular polarization with low axial ratio in a wider band than can be normally achieved with single element microstrip antennas with standard topologies.

In most antenna applications only parameters related to the amplitude of the far field require the designer analysis. However, when an antenna element is used as a feeder of a reflectarray, a crucial issue associated with the reflectarray performance is the feeder phase center position. In this case, it is essential to know the phase center position to complete the characterization of the feeder.[9–11]

This paper proposes an approach for the design of a circularly polarized array with sequential rotation. The main feature of the proposed design approach is the optimization of the axial ratio bandwidth without the need to redesign the feeding network. Wider axial ratio bandwidth is achieved in comparison to results reported in the literature for single layered microstrip antenna arrays. Moreover, the phase center position of the array is evaluated using a parametric analysis of the far field phase in the solid angle of interest for the reflectarray application. The optimization search is carried out in the 3D space, that is, *x*, *y*, and *z* directions.

To prove the concept, a 2 × 2 array of corner-truncated patches to be used as a K-band (18.7-19.2 GHz) reflectarray feed is presented.

2 | ANTENNA DESIGN

2.1 | Design of antenna element

The single antenna element is illustrated schematically in Figure 1A. The geometry considered for the array element is the well-known microstrip square patch with 2 truncated corners. It has been designed to operate at a central frequency f_0 = 18.95 GHz and with right-hand circular polarization (RHCP). The excitation is implemented by a microstrip quarter wave transformer to yield an input impedance of 100 Ω. A 0.787 mm thick RT/Duroid 5880 substrate with relative permittivity 2.2 and loss tangent 0.001 was chosen. The single element design consisted of 2 steps. First,

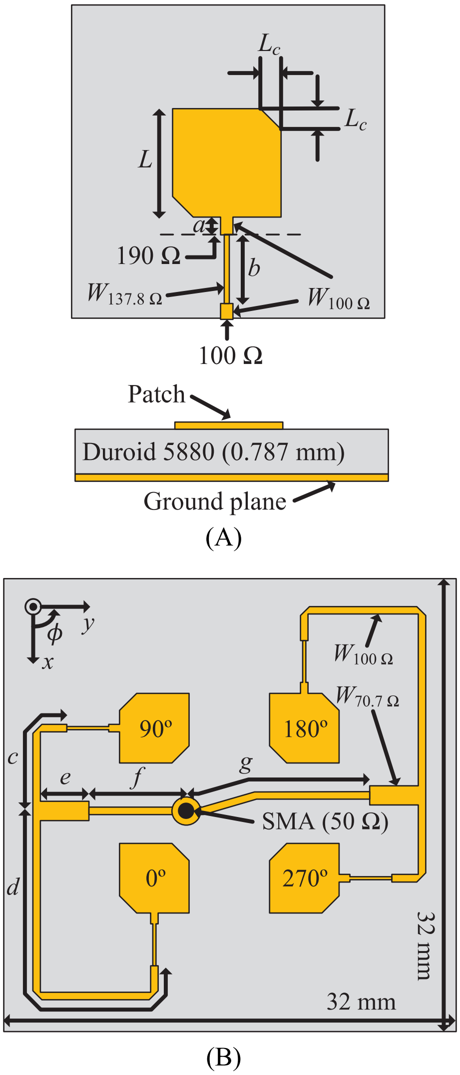

FIGURE 1 Geometry of the antenna element and array: (A) single element; (B) 2 × 2 array [Color figure can be viewed at wileyonlinelibrary.com]

the predesign of patch dimensions were quickly established using Estimate tool of Ansoft Designer software. Second, the predesigned patch dimensions as well as the microstrip feed was simulated and optimized with ANSYS HFSS, resulting in the following dimensions (in mm): $L = 4.677$, $L_c = 0.888$, $a = 0.766$, $b = 2.961$, $W_{137.8\Omega} = 0.217$, and $W_{100\Omega} = 0.530$.

2.2 | Array design

The array is composed of 4 elements in a 2 × 2 configuration as shown in Figure 1B. The elements are separated 10.607 mm (0.67 λ_0) from each other aiming at maximum gain without producing large side lobes. The design is based on the sequential rotation, whereby the elements are sequentially rotated by 90° relative to the adjacent elements. The feeding network shifts the phase of each excitation by 90°, which is a generalization of the procedure necessary to obtain circular polarization from linearly polarized elements.

The sequential rotation technique has been chosen because it provides an improvement of the axial ratio bandwidth and radiation pattern symmetry.[5] The design and optimization of the array dimensions have been carried out also using ANSYS HFSS. The optimized array geometric parameters (in mm) are: $c = 7.378$, $d = 23.081$, $e = 3.432$, $f = 6.877$, $g = 13.127$, and $W_{70.7\Omega} = 1.360$. Simulated axial ratio (in the broadside direction) and input reflection coefficient results for the ideal feed case, that is providing relative phases 0°, 90°, 180°, and 270° in the whole frequency range, are shown in Figure 2. In Figure 2B, for the ideal feed case, only the curve relative to the array element with 0° relative phase is shown because the other 3 elements have very similar results.

The simulated results, also shown in Figure 2 for the array with the real feed, indicate 1.38 GHz (7.28%) 3-dB axial ratio bandwidth and 1.9 GHz (10.02%) impedance bandwidth ($|\Gamma| < -10$ dB) which satisfy the specifications. However, the integration of the feeding network in a coplanar configuration yields performance degradation, especially in terms of axial ratio, due to spurious radiation and coupling between the lines and the patches. Moreover, the electrical length of the feeding section of each array element changes with frequency and therefore the corresponding feed phase also changes.

In order to mitigate this problem, a scaling approach can be used to optimize the patch dimensions so as to improve the performance. This technique consists of 2 steps: in the first step, the dimensions of the truncated corners are varied to optimize the axial ratio level, even though this is achieved in a frequency different from f_0. Parametric simulations varying the dimensions of the truncated corners have been carried out and the results are presented in Figure 2, where Δ stands for the deviation of L_c from the initial value (0.888 mm). In this case, there was an improvement of the axial ratio only for positive Δ values. The best axial ratio value was obtained at $f_{best} = 19.9$ GHz when L_c is increased by 0.25 mm. In the second step, this point must be shifted to f_0. This can be easily achieved by applying a scaling factor X, which is defined as the ratio between f_{best} and f_0, given by

$$X = \frac{f_{best}}{f_0} \quad (1)$$

where $X = 1.0501$ in this case. The frequency shift is finally realized by scaling the dimensions (L, L_c) of the patch with the factor X.

2.3 | Phase center evaluation

Basically, the computation of the phase center position consists in moving the reference point O (initially located at the array geometrical center) in x, y and z (Δx, Δy, Δz) aiming to provide a spherical wave surface or, in another words, a constant phase curve in an angular aperture θ_A, as shown in Figure 3. In other words, the phase center is here defined as

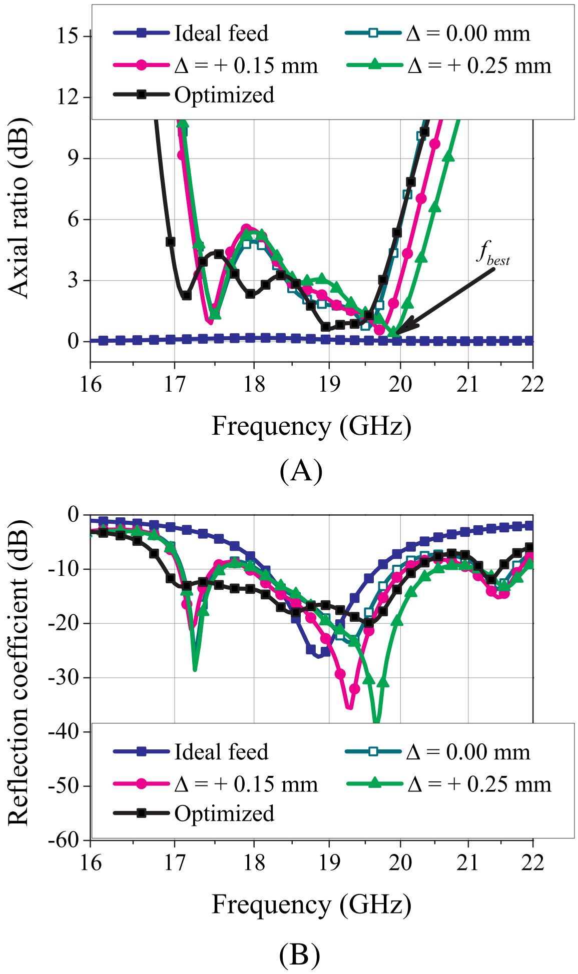

FIGURE 2 Antenna array simulation results: (A) axial ratio; (B) input reflection coefficient [Color figure can be viewed at wileyonlinelibrary.com]

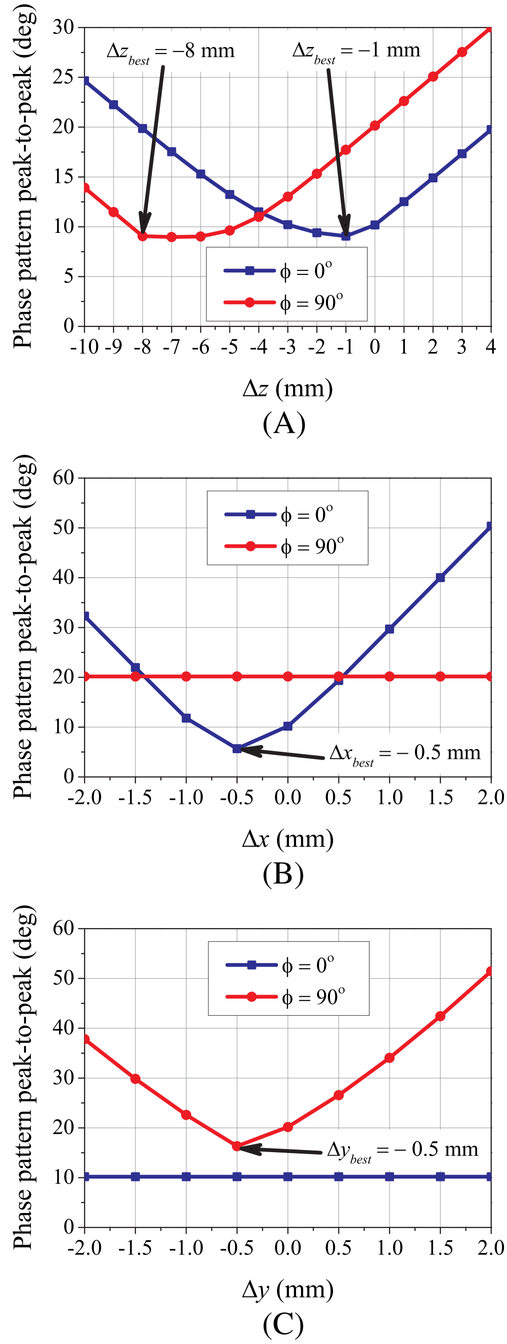

FIGURE 4 Peak-to-peak phase variation for different *x*, *y*, *z* positions: (A) variation along *z*-direction; (B) variation along *x*-direction; (C) variation along *y*-direction [Color figure can be viewed at wileyonlinelibrary.com]

the point that minimizes the phase pattern variation over the angular region $-27° < \theta_A < +27°$, which corresponds to the illumination of the reflectarray aperture (for F/D = 1).

In order to find the phase center position of the antenna array, parametric simulations are presented in Figure 4, where one can see the peak-to-peak variation of the phase pattern for RHCP on 2 cuts ($\phi = 0°$ and $90°$) as a function

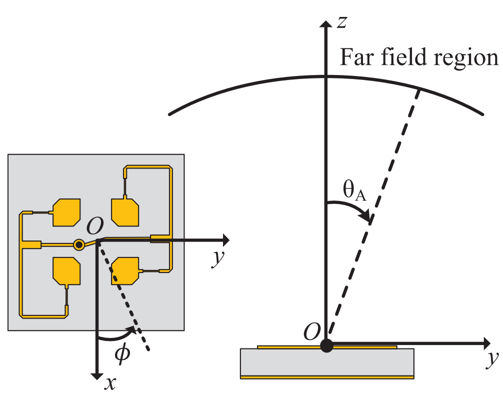

FIGURE 3 Schematic diagram for phase center evaluation [Color figure can be viewed at wileyonlinelibrary.com]

of the position (Δx, Δy, and Δz) operating at central frequency f_0. The lower peak-to-peak phase variation leads to the best phase center estimation, as in the case of an ideal spherical wave no variation at all occurs. First, parametric simulations just moving the reference point along *z*-direction have been carried out and the results are shown in Figure 4A. As it can be seen, there are different optimal phase center positions for each cut ($\phi = 0°$ and $90°$), corresponding to $\Delta z = -1$ and $\Delta z = -8$ mm, respectively. Thus, it is necessary to find a trade-off between these 2 phase

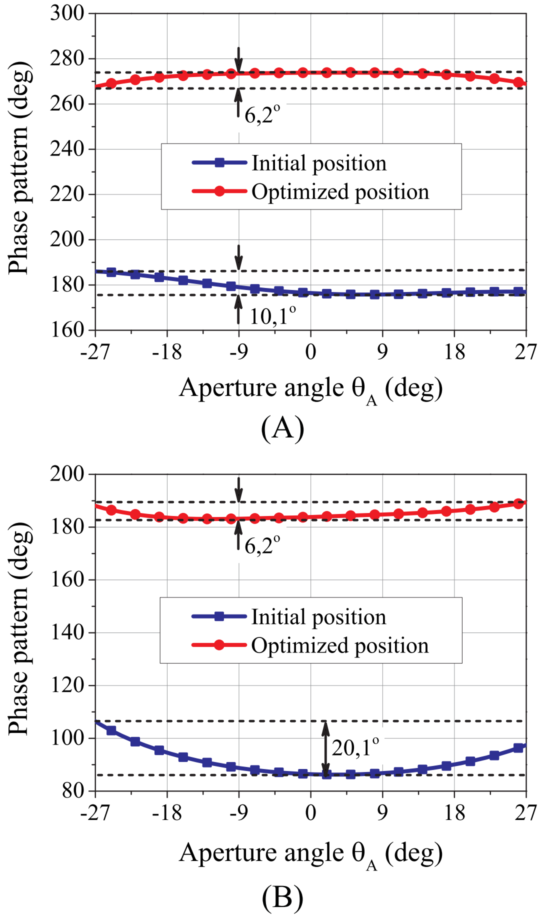

FIGURE 5 Phase pattern for initial and optimized phase center positions: (A) $\phi = 0°$; (B) $\phi = 90°$ [Color figure can be viewed at wileyonlinelibrary.com]

center positions along the *z*-direction. Other parametric simulations are considered along the *x*-direction ($\phi = 0°$) and *y*-direction ($\phi = 90°$), whereby both cases yielded best responses of phase pattern at −0.5 mm, as illustrated in Figure 4B,C, respectively. It is worthwhile to notice that no variation of phase pattern has been verified for cuts $\phi = 90°$ and 0° considering displacements along the *x*- and *y*-direction, respectively. From these parametric simulations, the best 3D position of the phase center can be considered to be (in mm) $\Delta x = -0.5$ $\Delta y = -0.5$, and $\Delta z = -4.28$.

To demonstrate the application of the previously estimated phase center position, curves of phase pattern for RHCP on 2 cuts ($\phi = 0°$ and 90°) as function of aperture angle $-27° < \theta_A < +27°$, considering initial and optimized positions are depicted in Figure 5. The simulated curves show that the initial position provided large phase variation within about 10.1° for $\phi = 0°$ and about 20.1° for $\phi = 90°$, whereas the optimized position resulted in a smoother phase fluctuation within about 6.2° for both cuts ($\phi = 0°$ and 90°). In addition, another significant requirement for the reflectarray feed is the phase center stability in the operating frequency band. It is noted that, the bandwidth of reflectarray antennas is also governed by the bandwidth of the used unit cells,[9] but the effect of the phase deviation of the feed is an essential consideration for designing reflectarray antennas, since any shift in the phase center position generates phase errors, which might limit the bandwidth by differential spatial phase delay[9] and, therefore, deteriorate performance. By considering the optimized position previously evaluated, curves of the peak-to-peak variation of the phase pattern for RHCP on 2 cuts ($\phi = 0°$ and 90°) as function of the frequency and aperture angle $-27° < \theta_A < +27°$ are shown in Figure 6A. For $\phi = 90°$ a large phase pattern variation is verified toward the lower frequency. In order to correct the response for $\phi = 90°$, a new optimization considering the aforementioned parametric analyses presented at Figure 4 has been considered. By analyzing the phase pattern illustrated in Figure 6A, one can see that it is possible to move the curve to a lower frequency by adjusting the position Δy. After that, small adjustments in positions Δz and Δx were considered, where the best 3D position of the phase center throughout the band can be considered to be (in mm) $\Delta x = -0.44$ $\Delta y = -0.27$ and $\Delta z = -4.48$. The new optimized position resulted in an improvement of phase fluctuation within about 9° for both cuts ($\phi = 0°$ and 90°) considering the entire operation band, as depicted in Figure 6B.

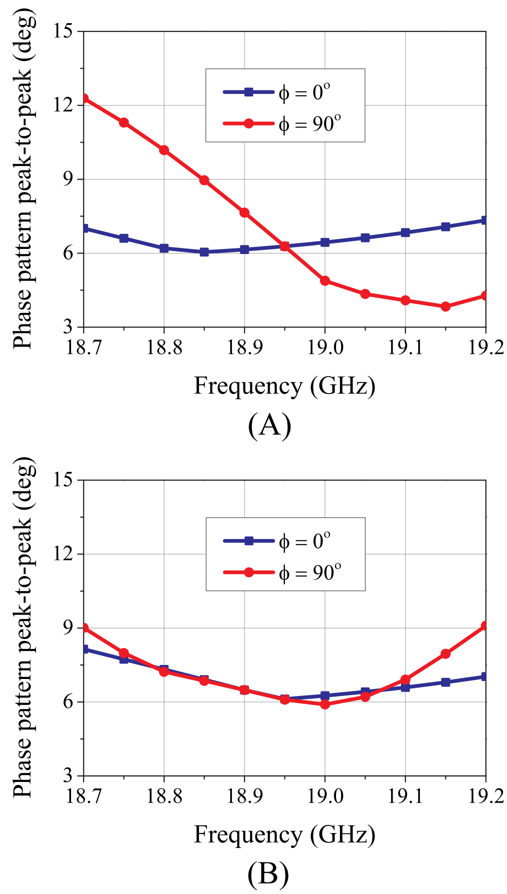

FIGURE 6 Peak-to-peak phase variation in the frequency operation band: (A) initial optimized position; (B) final optimized position [Color figure can be viewed at wileyonlinelibrary.com]

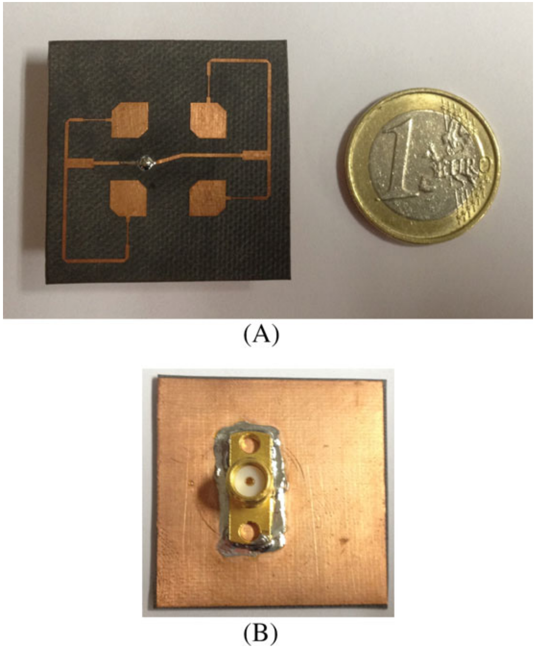

FIGURE 7 Photographs of the antenna prototype: (A) top view; (B) bottom view [Color figure can be viewed at wileyonlinelibrary.com]

3 | EXPERIMENTAL RESULTS

A prototype of the optimized antenna has been fabricated (Figure 7) and tested. The simulated and measured axial ratio and input reflection coefficient results are shown in Figure 8. The corresponding bandwidths (for AR < 3 dB and $|\Gamma| < -10$ dB) are 3.78 GHz (19.94%) and 2.67 GHz (14.1%), respectively.

Regarding phase center position, simulated and measured data of phase pattern for RHCP, on the principal planes considering an aperture angle of $-27° < \theta_A < +27°$, operating at central frequency f_0, have yielded results in excellent agreement for the initial position ($x = y = z = 0$), as show in Figure 9. It is observed that the experimental results for the optimized phase center position are not evaluated. However, they can be extrapolated from the simulated data for the optimized position.

The simulated and measured realized gain patterns at 18.95 GHz are shown in Figure 10. The boresight gain is 12.5 dBi and the deviation between simulated and measured values, for the RHCP component, is <0.35 dB. The side lobe and the boresight cross polarization levels are below −11.85 and − 18.1 dB, respectively. Moreover, the radiation pattern main lobe is almost rotationally symmetric and the boresight gain changes <0.5 dB in the whole operation band.

An overall good agreement between simulated and experimental results is obtained for the fabricated prototype.

A comparison between the proposed antenna and previously published antennas exhibiting similar complexity and with either corporate or series feeding networks is summarized in Table 1. The 3-dB axial ratio and the impedance bandwidths of the proposed array antenna are significantly larger than the ones reported in Refs. 5–8. The difference is particularly relevant when the same type of corporate feed is used. Comparing with[6] the axial ratio and impedance bandwidths are improved by a factor of 2.73 and 2.89, respectively.

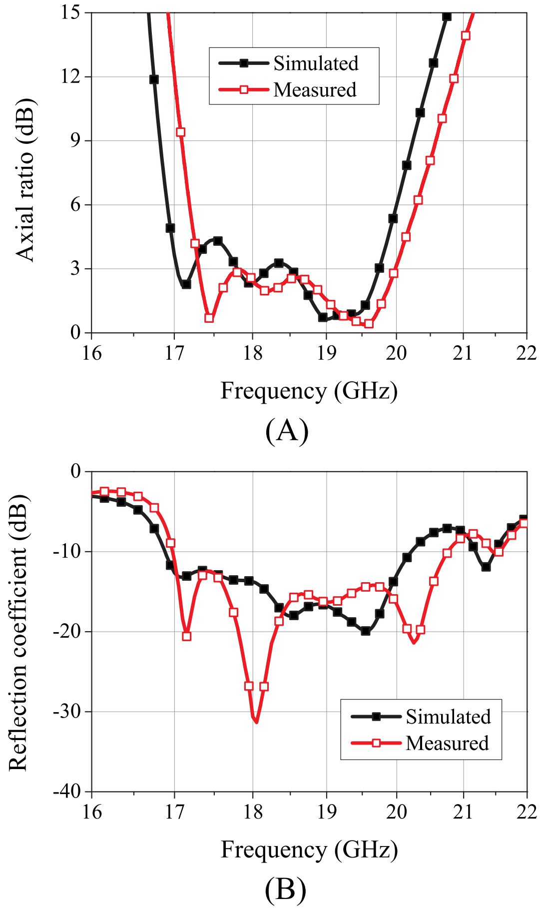

FIGURE 8 Comparison of simulated and measured results: (A) axial ratio; (B) input reflection coefficient [Color figure can be viewed at wileyonlinelibrary.com]

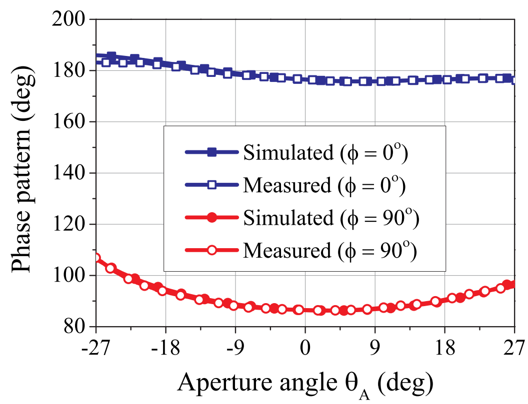

FIGURE 9 Simulated and measured phase pattern for initial phase center position at 18.95 GHz [Color figure can be viewed at wileyonlinelibrary.com]

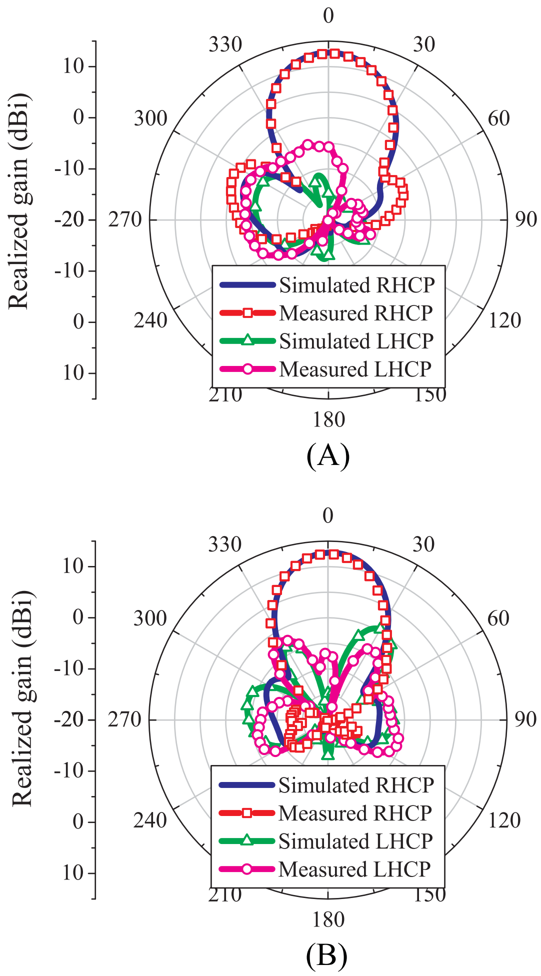

FIGURE 10 Comparison of simulated and measured radiation patterns (gain scale) at 18.95 GHz: (A) $\phi = 0°$; (B) $\phi = 90°$ [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Performance comparison with other published array antennas

Design	Type of feed	Frequency (GHz)	Bandwidth (%) Axial ratio	Return loss
Evans et al.[5]	Series	5.8	3.4	9.8
Evans et al.[6]	Corporate	5.8	5.17	6.89
	Series	5.8	12.4	14.7
Jazi and Azarmanesh[7]	Corporate	2.45	0.61	2.55
	Series	2.45	0.81	2.97
Chen et al.[8]	Series	29	5.44	15.82
This work	Corporate	18.95	14.1	19.94

Concerning gain, series feed arrays tend to provide slightly higher values[8] but the radiation pattern is less stable in frequency.

4 | CONCLUSION

This letter presented a circularly polarized 2×2 microstrip antenna array with sequential rotation of elements and corporate feeding for application as a reflectarray feed. A simple design approach based on a scaling technique has been proposed to increase the operation axial ratio and impedance bandwidths of microstrip arrays with sequential rotation of elements. For the same type of corporate feed the axial ratio and impedance bandwidths are at least almost 3 times larger than previously proposed configurations. Due to its simplicity and effectiveness, this method has demonstrated to be an efficient tool for antenna engineers, since redesign the feeding system is not needed. Moreover, a set of parametric analysis by moving the reference point on the 3 axes (x, y, z) to determine the optimized phase center position of the 2×2 array was presented. The optimized phase center position for the operating band provided good results with phase pattern fluctuation within about 9° for both principal planes. The simulated and measured phase patterns for both principal planes operating at central frequency and considering initial position showed very good agreement.

The general good agreement obtained between numerical simulation and experimental results has validated the design approach and provided proof of the proposed concept. Moreover, the good performance achieved demonstrates that the 2×2 array of corner-truncated patches introduced in this paper can be used as a reflectarray feed operating at K-band.

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