Compact Circularly Polarized Patch Array Antenna

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***Abstract*—A circularly polarized (CP) patch array antenna with compact size is proposed in this letter. The proposed radiation element consists of 2 × 2 partly overlapped square patches and one cross-shape slotted substrate integrated waveguide (SIW) cavity with four feeding ports. Stacked structure is adopted for the sake of a compact size and convenient integration with active circuits. Sequential rotating technique is adapted and applied to the radiation element with two-dimensional symmetry to enhance axial-ratio bandwidth performance. The subarray can realize a gain of 11 dBic at 23.6 GHz with the radiation efficiency up to 90%. A prototype array antenna with four subarrays is designed and fabricated to validate the proposed method using low-cost multilayer printed circuit board (PCB) process. Experimental results on reflection coefficient, axial ratio, and gain agree well with simulation results. The prototype array antenna can function well from 23 to 24.2 GHz (5%) with its reflection coefficient under −13 dB and its axial ratio under 3 dB. A maximum gain of 16 dBic can be obtained at 23.3 GHz.**

***Index Terms*—Array antenna, circular polarization (CP), sequential rotating technique, substrate integrated waveguide (SIW).**

I. Introduction

VARIOUS types of patch antennas have been investigated and widely utilized in modern wireless communication systems over the last decade due to their advantages of low cost, low profile, light weight, and convenient integration with active circuits [1]. Among the patch antennas, circularly polarized (CP) antennas are especially attractive in point-to-point communication systems since polarization tracking and alignment could be avoided [2].

Sufficient impedance and axial-ratio (AR) bandwidth, high gain, and compact size are the main concerns in CP antenna designs in order to meet the requirements of practical applications. Many methods have been proposed to enhance the inherent narrow impedance and 3-dB axial-ratio bandwidth of conventional patch antennas, such as adopting stacked structure [3], [4] and sequential rotating technique [5]–[8].

Sequential rotating technique is quite an effective method to improve the antenna performance, with the radiation patches sequentially rotated not only in space but also in phase. There are also many reported works on the sequential phase shifting networks [7], [8]. In previous research using sequential rotating technique, four paths with the same amplitudes and 90° phase differences in the sequential feeding network are connected to four rotated CP radiation elements correspondingly. Then, the radiation elements form an array and generate desired CP radiation with great improvement on the axial-ratio bandwidth due to the extra symmetry in configuration.

In this letter, a compact radiation element of 2 × 2 partly overlapped patches backed by a cross-shape slotted substrate integrated waveguide (SIW) cavity with four feeding ports is proposed using stacked structure. The energy coupled out from the slotted cavity is used to illuminate all the patches other than using physical connections, resulting in a compact design. Sequential rotating feeding network is adapted and placed under the patches around the cavity in order to improve the axial-ratio bandwidth performance. Unlike previous approaches, sequential phase shifting excitations are applied to one single radiation element with two-dimensional symmetry, other than four separate and rotated CP radiation elements, which also contribute to a compact realization. A prototype antenna with four subarrays is designed and fabricated around 24 GHz to validate the proposed design.

This letter is organized as follows. In Section II, the structure and operating principle of both the proposed radiation element and the subarray will be presented. In Section III, the simulated and experimental results on reflection coefficient, gain, axial ratio, and radiation patterns of the subarray and the prototype array will be provided and discussed. Finally, the conclusion will be made in Section IV.

II. Design of the Proposed Array

In this section, both the radiation element and phase shifting network of the proposed CP antenna will be discussed. All the simulations are performed using Ansoft HFSS software, with dielectric and conductor losses taken into consideration.

Layer configuration of the multilayer printed circuit board (PCB) process is presented in Fig. 1. The microwave substrates used in the design are Rogers 5880 with ε_r equal to 2.2 and Rogers 3001 with ε_r equal to 3. Two dielectric layers of Rogers 5880 are bonded together using bonding film Rogers 3001. All the metal layers are made of copper with the thickness of 0.018 mm. The cross-shape slotted SIW cavity is formed in the second dielectric layer by blind vias (Via II), with the cross-shape slot on the middle metal layer and four microstrip feeding lines on the bottom metal layer. Partly overlapped patches are placed on the top metal layer and excited by the slotted cavity.

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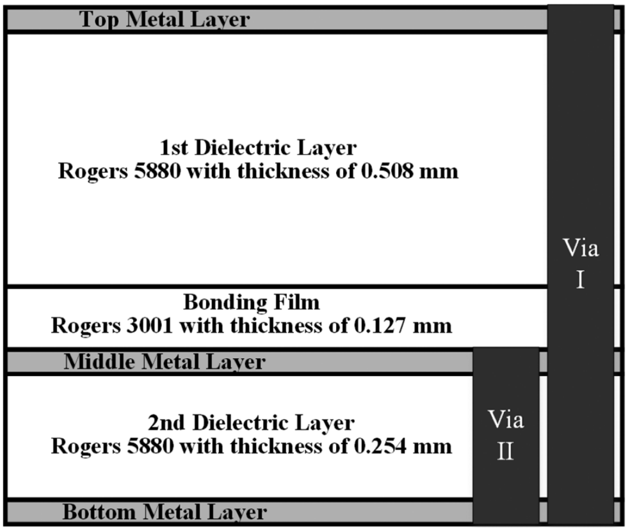

Fig. 1. Layer configuration of the proposed CP antenna.

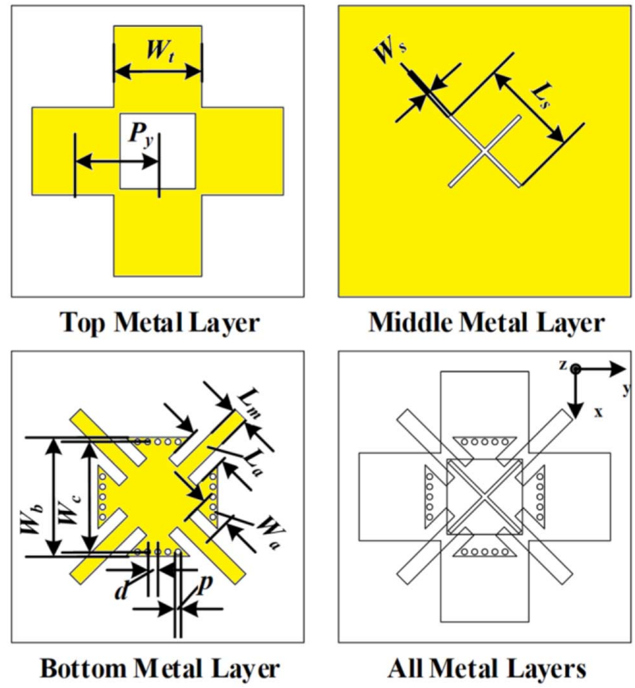

Fig. 2. Configuration of the proposed radiation element (yellow color for metal surface, and white color for exposed substrate).

A. Radiation Element

The proposed radiation element consists of four partly overlapped square patches and one cross-shape slotted SIW cavity fed by four microstrip lines, as shown in Fig. 2 with all its dimensions marked. Generally, the proposed structure can be divided into the four radiating patches and the cross-shape slotted SIW cavity with four feeding ports. The four patches on the top metal layer are partly overlapped in order to obtain a compact size, low sidelobe level, and good cross-polarization suppression in case of linear polarization [9]. Microstrip feeding ports are preferred for convenient integration with active circuits on the bottom layer, and the cross-shape coupling scheme brings in a good separation between the radiation patches layer and the circuits on the bottom layer.

Since the configuration of the radiation element is two-dimensional symmetric, all the stacked patches can be excited by any one of the four feeding ports and generate a linear polarized radiation along the feeding direction. The realized gain with one feeding port is around 8 dBi. By adding an excitation with 180° phase shift to the port at the opposite side of the original excitation, 3-dB gain enhancement can be obtained, and stable linearly polarized radiation at the broadside direction can be ensured. Under the circumstances, the energy leaked to the orthogonal feeding ports by the differential excitations are out of phase and can be canceled off. Thus, the cross-polarized radiation will be further suppressed. This analysis also applies to the other two ports. By applying a pair of differential excitations at the other two ports, orthogonally polarized radiation with the same realized gain can be obtained.

The proposed radiation element can be used to realize either linear or circular polarization by combining the proposed radiation element with corresponding feeding network. In this letter, circular polarization is achieved by applying sequential phase-shifting feeding network to the radiation element. The excitations of the four feeding ports need to be set sequentially shifted by 90°, clockwise [right-hand CP (RHCP)] or anti-clockwise [left-hand CP (LHCP)]. Then, the CP radiation can be achieved with the combination of the two orthogonally linear polarizations.

Sequential phase-shifting technique employed in the proposed design is different from the conventional sequential rotating technique. The conventional technique brings in extra symmetries into the subarray and improves the axial-ratio bandwidth by applying sequential phase-shifting excitations to each rotated CP radiation elements. The sequential phase-shifting mechanism employed in this letter directly applies the sequential phase-shifting excitations to one single radiation element, which results in a more compact realization. Moreover, good axial-ratio bandwidth can be obtained with the quadrature phase excitations in the feeding network and the inherent good symmetry of the configuration.

In this letter, the sequential phase-shifting feeding network is realized by using T-junction power dividers shown in Fig. 3. The phase-shifting property is achieved by offsetting the T-junction from the center of the branch microstrip lines, which is the principal limitation of the axial-ratio bandwidth.

Thanks to the stacked structure of the subarray, the sequential phase-shifting feeding network can be placed around the SIW cavity under the stacked patches, with one microstrip excitation port provided. Thus, larger arrays can be obtained by simply adding more power-dividing circuits, as shown in Fig. 4

For the CP subarray with the dimensions shown in Table I, simulated results on the reflection coefficient, gain, axial ratio, and radiation patterns are provided in Figs. 5 and 6, respectively. The proposed subarray can realize an RHCP radiation and achieve a gain of 11 dBic at 23.6 GHz with radiation efficiency up to 90%. The operating bandwidth is 22.95–24.25 GHz (5.5%) with its reflection coefficient under −20 dB and the axial ratio under 3 dB. The sidelobe levels are quite low since the

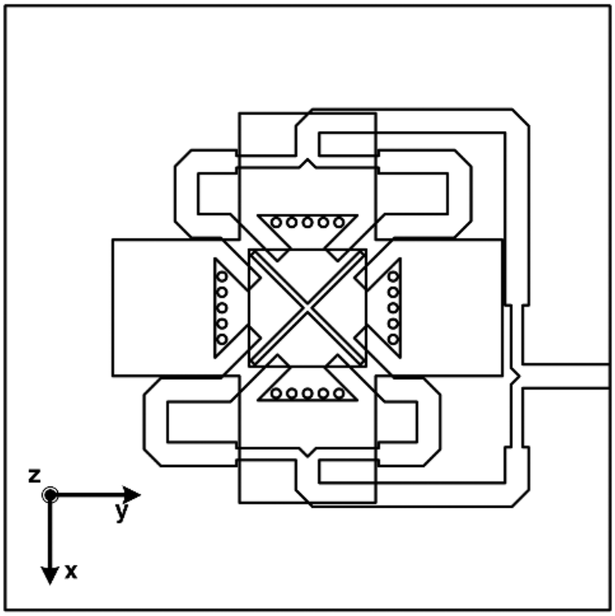

Fig. 3. Configuration of the 2 × 2 patch subarray with circular polarization.

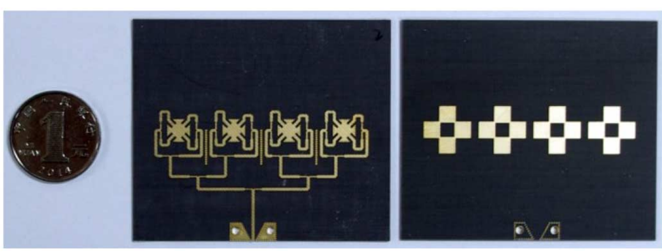

Fig. 4. Photograph of the prototype patch array antenna.

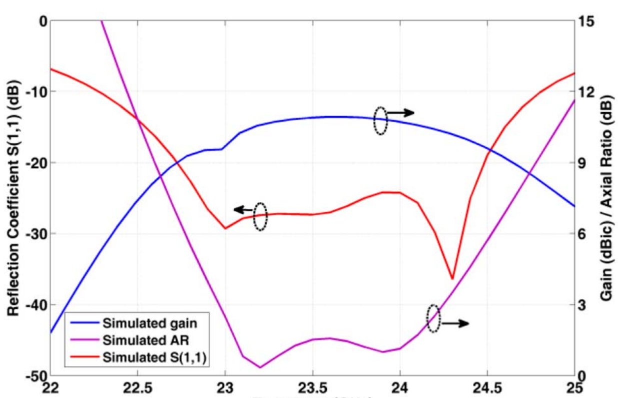

Fig. 5. Simulated results on the reflection coefficient, gain, and AR of the CP subarray.

TABLE I
DIMENSIONS OF PROTOTYPE

Symbols	W_b	W_c	W_a	W_s
Values [mm]	6.12	5.66	1.53	0.2
Symbols	P_y	W_t	L_a	L_s
Values [mm]	8.38	4.51	2	5.12
Symbols	L_m	d	p	
Values [mm]	0.78	0.3	0.52	

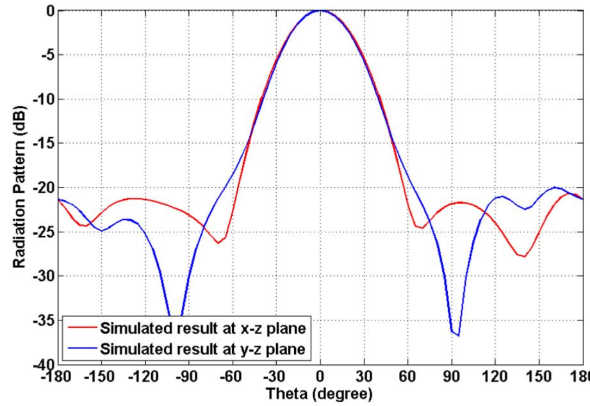

Fig. 6. Simulated radiation pattern results of the CP subarray at 23.6 GHz.

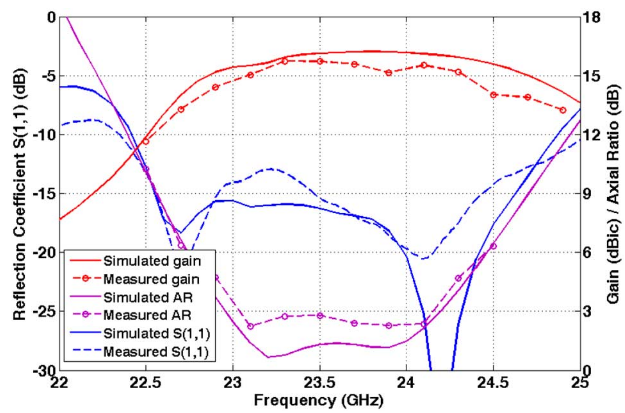

Fig. 7. Simulated and measured results on the reflection coefficient, gain, and AR of the prototype array antenna.

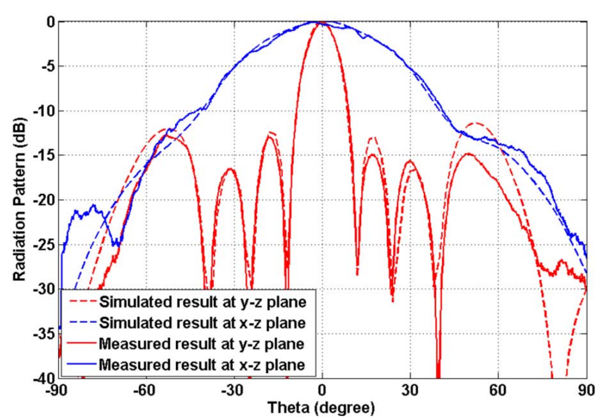

Fig. 8. Simulated and measured radiation patterns of the prototype array antenna at 23.3 GHz.

distance between adjacent patches is around half-wavelength in free space.

III. Results and Discussion

A prototype CP array antenna with four subarrays is designed and fabricated to validate the proposed design. The overall size of the prototype antenna shown in Fig. 4 is 70 × 60 mm^2.

Simulated and experimental results of the prototype array are also provided, with reflection coefficient, gain, and axial ratio shown in Fig. 7 and radiation patterns shown in Fig. 8. The prototype patch array antenna with four subarrays can function well from 23 to 24.2 GHz (5%) with its reflection coefficient under -13 dB and its gain varied from 15 to 16 dBic. The RHCP main beam is stable at its broadside with a maximum gain of 16 dBic at 23.3 GHz.

IV. Conclusion

A circularly polarized patch array antenna with a compact size is presented in this letter. Unlike conventional sequential phase-rotating technique, phase-shifting feeding network in the proposed antenna design is applied directly to a single radiation element with four feeding ports and excellent two-dimensional symmetry. A good bandwidth performance can be realized by the symmetry of the radiation element and the quadrature phase excitations. A prototype patch array antenna with four elements is designed and measured, validating the proposed design method. Compact sequential phase-shifting feeding networks and polarization-agile antennas are the potential improvements of the proposed design.

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