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Wideband Metamaterial Crossed-Arm Unit Cell for the Design of Beam-Scanning Circularly Polarized Reflectarray Antenna

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***Abstract*—This paper presents a reconfigurable metamaterial unit cell using crossed arms and its application in designing a wideband beam-scanning circularly polarized (CP) reflectarray (RA) antenna. The unit cell is composed of two pairs of reconfigurable rotated crossed-arms. One pair is connected by two line strips, and the other pair is connected by two arc-shaped strips. The unit cell is verified with a wide CP reflection bandwidth of 7.7-15.5 GHz. An equivalent circuit is utilized to illustrate its working principle for wide CP reflection bandwidth. Based on this metamaterial unit cell, a wideband CP RA antenna was designed, developed, and tested for the initial performance verification. A high gain of 26.3 dBic and aperture efficiency of 58.3 % are obtained for this fabricated RA antenna. In addition, a wide axial ratio bandwidth of 7.6-15.9 GHz is achieved for the high gain unidirectional CP radiation.**

***Index Terms*—Circularly polarized antenna, metamaterial unit cell, reflectarray antenna, wide bandwidth.**

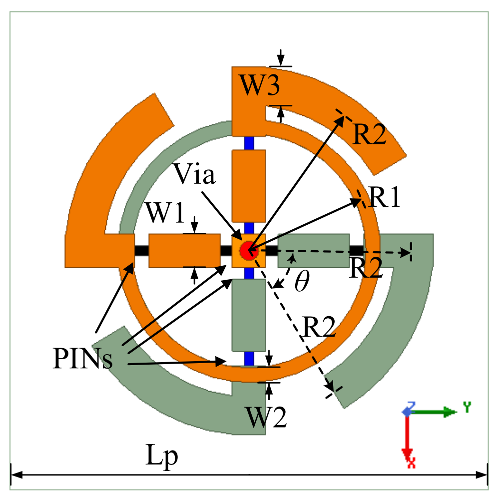
I. Introduction

Owing to the engineered electromagnetic characteristics, metamaterial structures have been widely applied in antenna designs, such as reflectarrays (RA), transmitarrays, intelligent reflective surface, etc. Because of the advantages of compact reflector, low-profile, light weight, and the spatial feed method, beam-scanning RA antennas are greatly welcomed in the high-gain required wireless communication systems, such as satellites, radars, and base stations [1].

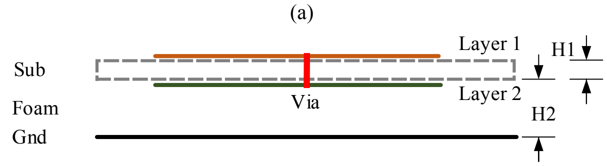
Traditional, the size-variable patches or strips can be utilized to realize the expected reflection phase for high gain RA antennas [2]-[5]. In [2], by varying the size of four-layered staked patches, a full 360° reflection phase delay is obtained, and a wide relative bandwidth of 30% is achieved for Ku-band satellite communications. In addition, by changing the length of an arc-shaped strip [4], a wide reflection phase range is achieved using only a single layer for both X and Ku band communications. However, it will be slightly different for realizing CP RA antennas depending on the fact that the feed of the reflector is linearly polarized [6]-[7] or circularly polarized [8]-[10]. In [6], the size-variable multi-layered T-shaped stubs are used to transform the linearly polarized wave into a CP wave. Therefore, CP radiation can be realized after the linearly polarized wave leaving the reflector. Due to the limitation of the conversion bandwidth, another method of the element rotation method is utilized to realize wide CP reflection bandwidth [8]-[10]. In [10], by using dumbbell-shaped subwavelength unit cell, the 3 dB gain bandwidth and CP bandwidth can be enhanced to 46.15%.

In this paper, a reconfigurable metamaterial unit cell composed of crossed-arms is presented and researched for the design of a wideband beam-scanning CP RA antenna. Two pairs of rotated crossed-arms are orthogonally arranged along x-axis and y-axis. Owing to the coupling between the crossed-arms, a wide CP reflection bandwidth of 7.7-15.5 GHz is achieved for the designed metamaterial unit cell. An equivalent circuit is utilized for working principle illustration. Finally, a wideband CP RA antenna was designed, fabricated, and measured for the first performance validation. A wide 3dB gain bandwidth of 43.7% and 3dB axial ratio (AR) bandwidth of 70.6% are achieved. These measured results show that the developed reconfigurable metamaterial unit cell can be a good candidate for wireless communication systems.

II. 1-Bit Metamaterial Unit Cell



(a)



(b)

Fig. 1. Configuration of the reconfigurable metamaterial unit cell. (a) Top view. (b) Side view.

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The configuration of the 1-bit reconfigurable metamaterial unit cell is shown in Fig. 1. As shown in the figure, it is composed of two pairs of rotated crossed-arms. The first pair is y-axis arranged with the arm directly connected by a via at the center. The second pair is x-axis arranged, the arms are connected to the first pair through two arc-shaped strips. Each pair of crossed arms is printed on a double-layered substrate. Note that there are four pin-diodes arranged on each pair of the crossed arms. At each of the control state, only black diodes or blue diodes are in conducting state (or in ON state). Commercial available substrate of Rogers 4003C with the thickness of 0.508mm and relative permittivity of 3.55 is used in the unit cell design. Key design parameters in the unit cell are, W1=0.7 mm, R1=2.6 mm, W2=0.3 mm, R2=3.5 mm, W3=0.8 mm, θ=59°, Lp=10 mm.

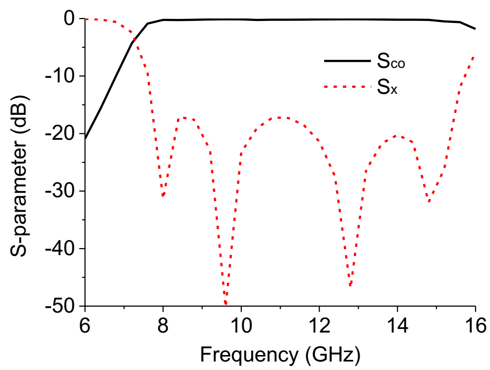

Fig. 2. The simulated S-parameters of the proposed unit cell when only black diodes are conducted.

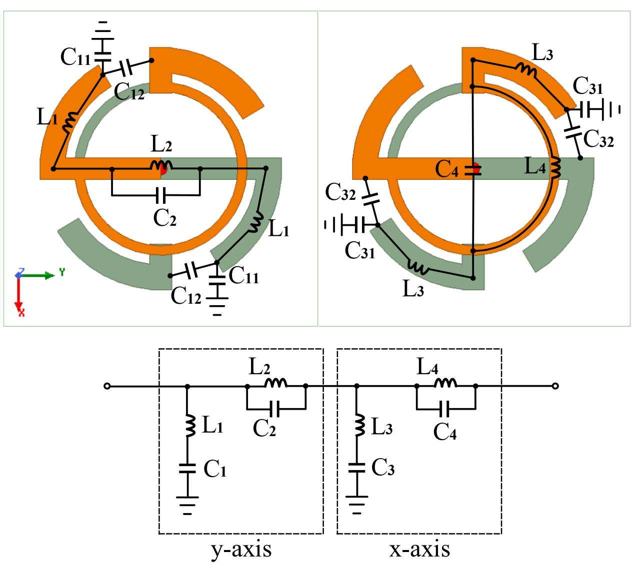

Fig. 3. A simplified equivalent circuit of the proposed metamaterial unit cell when only black diodes are conducted.

Fig. 2 shows the simulated S-parameters of the 1-bit unit cell under a normal impinged CP wave, which is obtained using the ideal periodical boundary in Ansys HFSS. It can be seen that a wide CP reflection bandwidth from 7.7 GHz to 15.5 GHz is achieved for the designed unit. In addition, four cross-polarized reflection zeros can be observed within the bandwidth.

A simplified equivalent circuit can be therefore obtained to illustrate its working principle, based on the coupling structure in the unit cell. The detailed equivalent circuit is shown in Fig. 3. Note the un-conducted diodes and strips are removed in the figure for the convenience of working principle illustration. It can be seen that the rotated arms at the periphery of the unit cell can be equivalent as the series resonances, which are shunt with the circuit. The center line strip or the arc-shaped strip can be equivalent as the parallel resonances, which are in series with the circuit. Therefore, benefiting the four different resonances in the unit cell, a wide CP reflection bandwidth with four cross-polarized reflection zeros is achieved for the designed reconfigurable metamaterial unit cell.

III. Verification

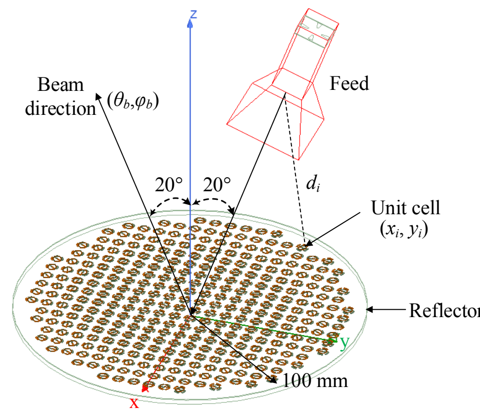

Fig. 4. Configuration of the proposed CP RA antenna.

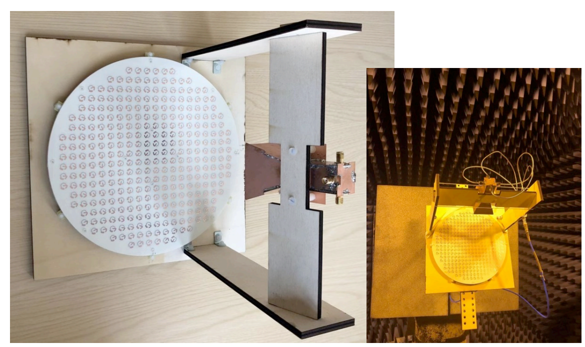

Fig. 5. Photographs of the fabricated CP RA antenna.

The presented unit cell is fist utilized to design a wideband unidirectional CP RA antenna, and then the beam-scanning performance will be verified afterwards. The configuration of the developed wideband RA antenna is shown in Fig. 4. This RA antenna is composed of 316 elements within a circular aperture. The diameter of the aperture is 200 mm. A wideband CP horn antenna is used to illuminate the designed RA reflector with the focal length of 180 mm. Note that the horn is offset 20° from the broadside, and the beam is also 20° offset but to the opposite direction to avoid the blockage of the beam.

This CP RA antenna was fabricated and tested at the University of Kent. Fig. 5 shows the photographs of the fabricated RA antenna and the antenna in the anechoic chamber for radiation pattern's measurement. Fig. 6 gives the measured AR of this RA antenna. A wide CP bandwidth of 7.6-15.9 GHz is achieved for AR<3 dB. Compared to the simulated AR, it has a slight shift to the upper frequency, but has a good accordance in the tendency.

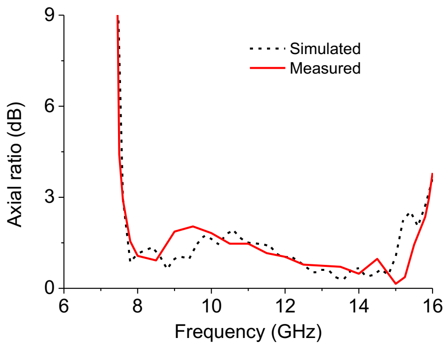

Fig. 6. Measured and simulated AR of the presented CP RA antenna.

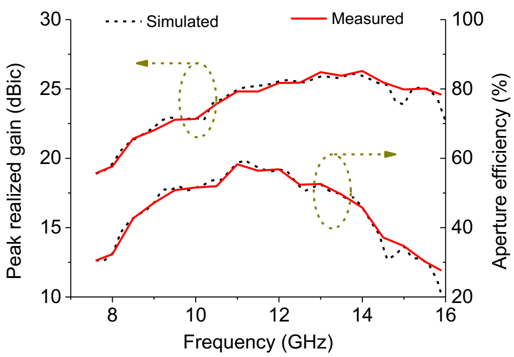

Fig. 7. Measured and simulated peak realized gains and aperture efficiencies.

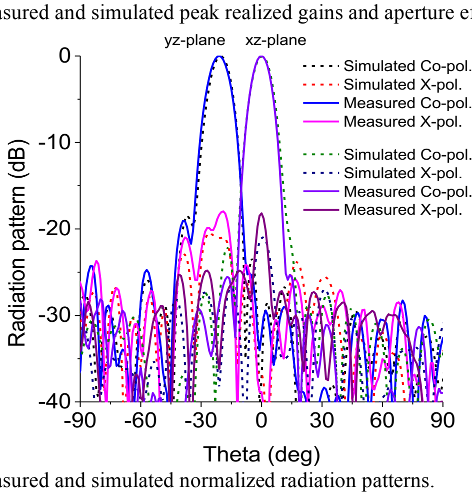

Fig. 8. Measured and simulated normalized radiation patterns.

The measured gain and AE are shown in Fig. 7. It can be seen that a maximum gain of 26.3 dBic is achieved at the frequency of 14 GHz, while a maximum AE of 58.3% is achieved at the frequency of 11 GHz. Fig. 8 gives the measured and simulated normalized radiation patterns at 10GHz. It can be seen, the main beam is -20° offset in yz-plane, just directed in the designed direction. The sidelobes are around 20 dB lower than the main beam in both two orthogonal planes.

IV. Conclusion

A new reconfigurable 1-bit metamaterial unit cell and its application in a wideband CP RA antenna are presented in this paper. The unit cell consists of two pairs of rotated crossed-arms, which are orthogonally placed on a double-layered substrate. The 1-bit phasing characteristic is controlled by the pin-diodes on the unit cell. Its wideband CP reflection bandwidth is analyzed by using an equivalent circuit, and the CP reflection bandwidth of 7.7-15.5 GHz is obtained for the developed unit cell. A wideband CP RA is then designed by sequentially rotating the unit cells for initial verification. Measured results prove that a wide 3dB gain bandwidth of 43.7% and a wide 3dB AR bandwidth of 70.6% are achieved for the designed CP RA antenna. In addition, high gain of 26.3 dBic and AE of 58.3% are obtained to ensure high performance for wireless communication systems.

Acknowledgment

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