Design of Single-Layer Circularly Polarized Reflectarray With Efficient Beam Scanning

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***Abstract*—This letter presents the design of wideband, low-cost, single-layer, ultrathin, beam-scanning circularly polarized reflectarray (CP-RA) antenna with high-radiation characteristics. To obtain efficient single and multiple CP beams, a subwavelength unit cell based on Pancharatnam–Berry (PB) geometrical phase was used to increase the beam scanning efficiency. PB unit cell with periodicity of 0.28λ_o and ultrathin thickness of 0.11λ_o is used to achieve the required phase correction across the reflectarray aperture to produce a collimated right-hand circularly polarized (RHCP) beam in the desired direction. The unit cell has three plasmonic resonances and the proposed CP-RA consists of 43 × 43 PB unit cells and occupies an area of 215 × 215 mm^2. Both simulation and experimental results show that the proposed CP-RA produces RHCP pencil-beam in the desired direction with a 1 dB gain bandwidth (BW) of 24.5% from 17 to 24.5 GHz, 3 dB gain BW of 46.15% from 15 to 24 GHz, peak aperture efficiency of 49.93%, 3 dB axial ratio (AR) of 46.15%. Furthermore, a beam scanning with 70° (±35°) scanning angle is achieved with gain scanning loss of less than 3 dB and beam squint of less than 1.3° within the whole frequency band and for all scanning angles.**

***Index Terms*—Antenna arrays, circular polarization, high gain, metasurface, periodic structures, reflectarray.**

I. Introduction

REFLECTARRAY antennas offer several advantages over the conventional parabolic reflector and they can combine the advantages of both a parabolic reflector and phased arrays [1]–[6]. A reflectarray transforms the phase front of the electromagnetic (EM)-wave radiated from a feed antenna (horn antenna) with spherical phase front to a planar phase front. To do this, reflectarray uses a 2-D array of properly spaced scatters (also called unit cells) having a carefully chosen reflection phase shift (or time delay) across the reflectarray aperture such that this 2-D array of unit cells can produce a directive collimated beam in the desired direction when it is illuminated by a suitably designed feed antenna [7]–[10]. In recent years, the design of circularly polarized (CP) reflectarrays (CP-RAs) has received increased interest. This interest primarily stems from the fact that CP-RAs have advantages of high gain, reduced polarization mismatch, and low multipath fading effect. Thus, CP-RA antennas are more desirable to be used in the modern satellite wireless communications system [11]–[18] because of their feasibility against environmental interferences. The required phase shift introduced at each unit cell across the CP-RA can be achieved either by changing the dimension of the metallic resonators [15], attaching true-time delay technique [16], or changing its angular rotation angle [7], [8]. In [15], a CP-RA with a unit cell of $\lambda/3$ grid spacing was proposed and 3 dB axial ratio (AR) of 11% and 1 dB gain bandwidth of 17% were achieved, respectively. In [17], CP-RA using a unit cell consisting of a microstrip patch connected to four phase delay lines was proposed with 10% and 15.5% 1 and 3 dB gain bandwidth, respectively, and 14.6% 3 dB AR were obtained. It has been noticed that most of the CP-RAs presented in the literature have single beam with applications of point-to-point communications. In other words, the beam-scanning capabilities of these CP-RAs have seldom been investigated or presented.

The multibeam or beam-scanning CP-RA antenna is an attractive high-gain antenna in both civilian and military wireless communication systems [19]–[23]. In [24], a CP beam-scanning reflectarray using elements of $\lambda/4$ periodicity was proposed and 31% 1.5 dB AR bandwidth, 32.8% 1 dB gain bandwidth, and ±15° beam-scanning range were achieved. A unit cell with spatial time-delay units was proposed in [25], and a CP-RA having 3 dB gain bandwidth of 40% and beam scanning range of ±45° was designed.

In this letter, the design of low-cost, high-efficiency CP-RA for high-gain right-hand circularly polarized (RHCP) single-beam and multi-RHCP-beams (beam scanning) is presented. The proposed CP-RA has a single layer of an ultrathin thickness (0.11λ_o). An efficient Pancharatnam–Berry (PB) geometrical phase unit cell of subwavelength periodicity (0.28λ_o) with three plasmonic resonances is used to achieve the required 360° phase range with very low loss. Both simulation and experimental results show that the proposed CP-RA can provide a 1 dB gain bandwidth (BW) of 24.5% from 17 to 24.5 GHz, 3 dB gain BW of 46.15% from 15 to 24 GHz, peak aperture efficiency of 49.93%, 3 dB AR of 46.15%. Furthermore, a beam scanning with 70° (±35°) scanning angle is achieved with gain scanning loss of less than 1.5 dB and beam squint of less than 1.3° within the whole frequency band. After detailed comparison with the previously published works, it is found that the proposed CP-RA has a better radiation characteristics (in terms of gain BW, AR, beam scanning, and efficiency) as a result of using very efficient meta-atom and the combination of the subwavelength unit cells (periodicity) and geometrical rotation phase.

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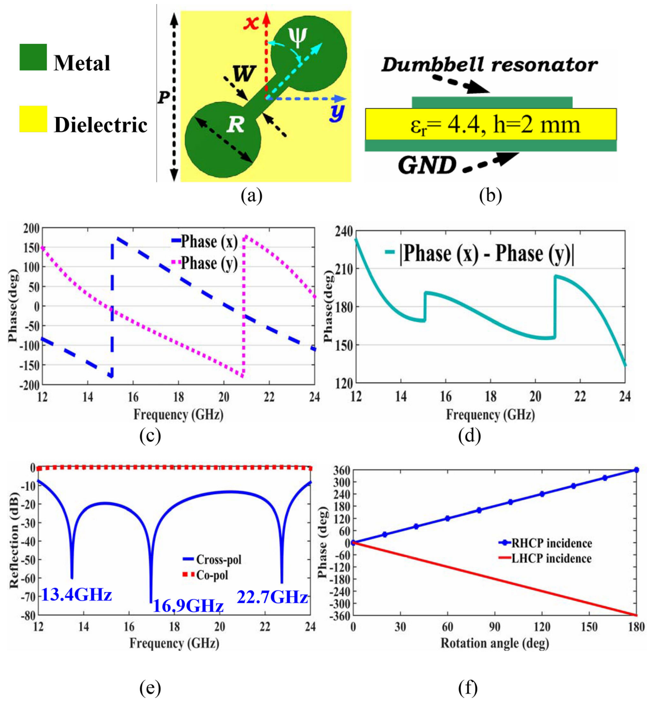

Fig. 1. (a) and (b) are layout of the PB unit cell. Reflection phase of the unit cell when illuminated by x- and y-polarized plane waves in (c) and their phase difference in (d). (e) co-pol and cross-pol reflection coefficients under CP incident wave. (f) Reflection phase versus rotation angle of the unit cell when illuminated by left-hand circularly polarized (LHCP) and RHCP waves.

II. PB Unit Cell Design

The topology of the proposed PB unit cell is shown in Fig. 1(a) and (b), which is composed of dumbbell-like copper resonator etched on the top side of FR4 dielectric substrate ($\varepsilon_r = 4.4$, $h = 2$ mm) with a solid metallic ground plane [26], [27]. The thickness of the copper layer of the resonator and the ground plane is set as 0.018 mm. The other geometrical parameters of the PB unit cell are: $P = 5$ mm, $R = 0.6$ mm, $W = 0.3$ mm. To assess the reflection characteristics of this PB unit cell, a series of electromagnetic numerical simulations were conducted using CST microwave studio. Fig. 1(c) shows the reflection phase of this unit cell when illuminated by x- or y-polarized waves, respectively [27]. As can be seen, the reflection phase is continuous and there is about $180° \pm 27°$ phase difference between x- and y-polarized reflections from 12.1 to 23.3 GHz, as shown in Fig. 1(d). According to PB phase theory, if the unit cell has a high reflection magnitude with nearly 180° (±27°) reflection phase difference between orthogonal linearly x- and y- polarized incidences, then when the unit cell is illuminated by a CP wave the cross polarized (cross-pol) reflection will highly reduce, leading to high copolarization (co-pol) reflection [28], [29]. In addition, reflection phase (φ) of the co-pol component can be expressed as $\varphi = \pm 2\psi$, where the polarization signs "–" and "+" correspond to LHCP and RHCP incident waves, respectively, and ψ is the rotation angle of the dumbbell-like metallic resonator with respect to x-axis. As shown in Fig. 1(e), the proposed PB unit cell has a high co-pol and low cross-pol reflections when it is illuminated by a CP wave with three plasmonic resonances at 13.4, 16.9, and 22.7 GHz, respectively. Furthermore, 360° co-pol reflection phase is achieved as shown in Fig. 1(f) when the rotation angle (ψ) increased gradually from 0° to 180° with step angle of 30°. Thus, this unit cell meets the demands of PB geometric phase theory and the unit cell is capable of reflecting the incident CP wave with abrupt reflection phase by angular rotation of the dumbbell-like copper resonator.

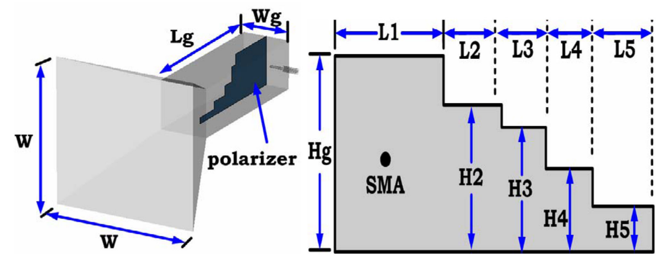

Fig. 2. Layout of the designed coaxial-fed RHCP horn antenna with: $L1 = 14$, $L2 = 1.89$, $L3 = 3.04$, $L5 = 6.33$, $Lg = 26$, Hg $= Wg = 11.3$, $H2 = 9.2$, $H3 = 5.64$, $H4 = 3.34$, $H5 = 1.5$, $W = 35$. All dimensions are in millimeters.

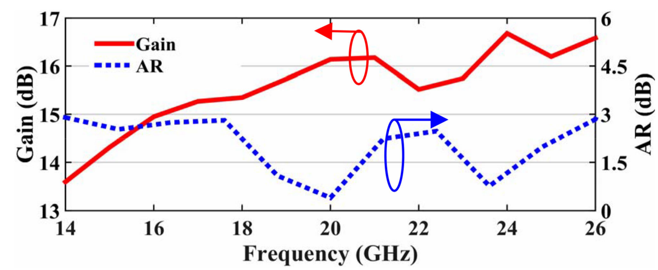

Fig. 3. Gain and AR of the RHCP horn antenna.

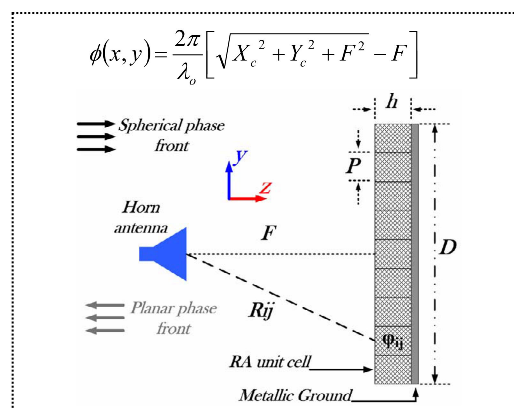

Fig. 4. Design principle of the proposed CP-RA.

III. Center-Fed CP-RA Design

A coaxially fed RHCP horn antenna is designed, and its gain and AR are carefully optimized to feed the proposed center-fed CP-RA. The layout of the designed RHCP feeder with the septum polarizer [30] is shown in Fig. 2 with all design parameters presented in the caption of Fig. 2. As can be seen in Fig. 3, the gain and AR show that the horn antenna can radiate RHCP wave from 14 to 24 GHz with AR of less than 3 dB within this frequency band. The design principle of the proposed center-fed CP-RA is shown in in Fig. 4. The CP wave radiated by the feeder with spherical phase front will illuminate the PB unit cells across the CP-RA aperture. By introducing a certain amount of

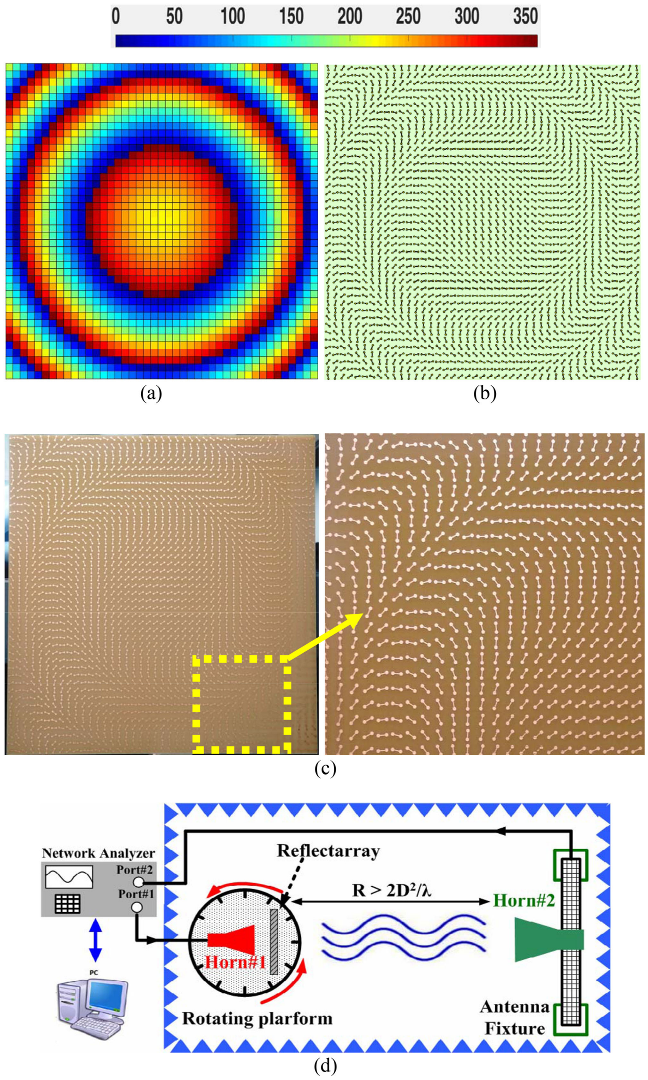

Fig. 5. (a) Computed required phase shift at each unit cell. (b) Layout of the designed reflectarray for simulation in CST Microwave Studio. (c) Photograph of the fabricated CP-RA prototype. (d) Far-field measurement setup.

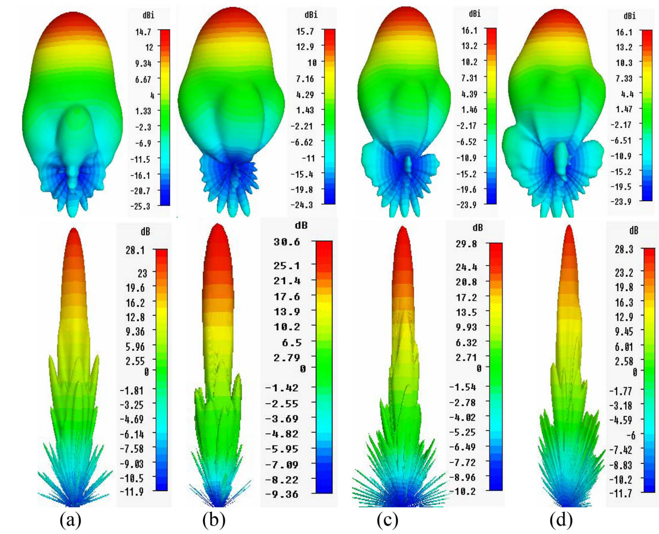

Fig. 6. Full-wave simulated 3-D far-field RHCP patterns of the horn antenna (upper row) and the CP-RA (lower row) at: (a) 15, (b) 19, (c) 21, and (d) 24 GHz.

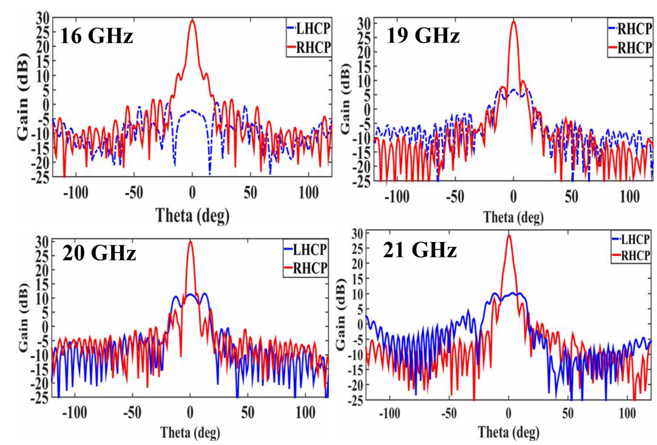

Fig. 7. Measured RHCP and LHCP radiation patterns of the CP-RA.

progressive phase shift $\phi\,(x,y)$ at each PB unit cell, a collimated directive beam with planar phase front will be reflected. The required phase shift at each PB unit cell can be obtained using the formula in Fig. 4, where X_c and Y_c are the coordinates of the unit cell in xy plane, F is the focal length, and D is the diameter of the CP-RA. The calculations of required phase shift at each unit cell are accomplished by a MATLAB script based on the formula in Fig. 4, and the result is presented in Fig. 5(a). It is important to point out that such kind of phase distribution was chosen for simplicity and another phase distributions are also possible. Based on the required phase shift, the angular rotation angle of the PB unit cells is determined using the data in Fig. 1(f), and the configuration of the constructed CP-RA is shown in Fig. 5(b). The CP-RA consists of 43×43 PB unit cells (1849 unit cells in total) with an aperture area of 215×215 mm^2 in xy plane. The RHCP horn antenna shown in Fig. 2 is used to feed the CP-RA and placed at a focal distance $F = 180$ mm ($F/D = 0.83$ with $D = 215$ mm). The dimensions of the feed horn and the proposed reflectarray are $1.98\lambda_o \times 1.98\lambda_o$ and $12\lambda_o \times 12\lambda_o$, respectively, and the blockage ratio is about 0.16. As shown in [37] and [39], when the blockage ratio is less than 0.2, the effect of the blockage will not be significant. Moreover, the blockage loss is also obtained from simulation when the reflectarray is illuminated by the horn antenna or its equivalent radiation pattern, and it has been noticed that the feed blockage loss is about 0.98–1.45 dB over the whole frequency band. The radiation characteristics of the CP-RA (with the feed horn) are investigated using the time domain solver in CST Microwave Studio. The 3-D far-field RHCP patterns of the CP-RA are presented in Fig. 6 along with the RCHP patterns of the feeder horn at the same frequencies for comparison purposes. It can be seen that collimated, highly directive RHCP pencil-beams are achieved in the boresight direction at all frequencies. A CP-RA prototype is fabricated using the printed circuit board (PCB) technology as shown in Fig. 5(c). Using the measurement setup shown in Fig. 5(d), the far-field RCHP and LHCP gain patterns of the CP-RA were measured inside an anechoic chamber and the results are shown in Fig. 7. The results show that the proposed CP-RA produces a focused RHCP pencil-beams (high gain beams) in the desired

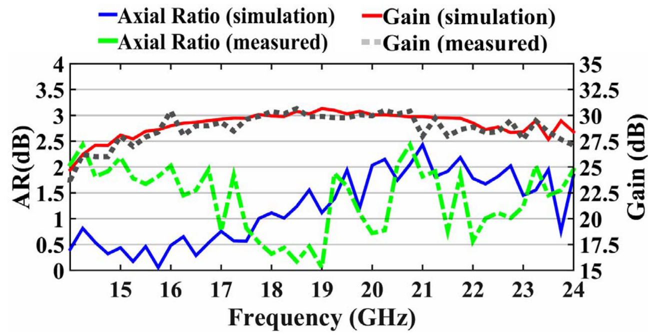

Fig. 8. Gain and AR of the proposed CP-RA.

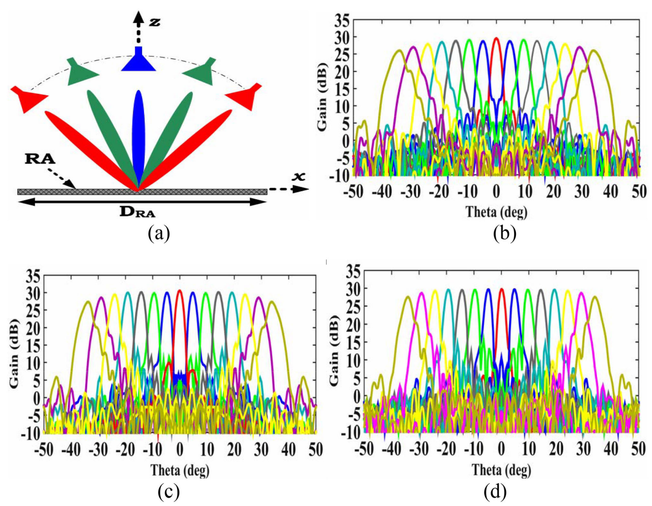

Fig. 9. (a) Mechanical beam scanning technique and the scanned beams at (b) 17, (b) 19, and (c) 21 GHz.

direction with the peak of sidelobe levels below −19 dB and maximum cross-polarization level of less than −20 dB over the entire frequency band of operation. As can be seen in Fig. 8, the RHCP gain bandwidth is about 24.5% from 17 to 24.5 GHz, 3 dB gain BW of 46.15% from 15 to 24 GHz, 3 dB AR is 46.15% from 15 to 24 GHz, peak aperture efficiency (AE) of 49.93% at 19 GHz calculated using the following formula: AE = (gain × λ^2 / 4π × area) where area represents the physical area of the CP-RA [31]–[34].

IV. Beam-Scanning Capability Investigation

It is always a design challenge to steer the beam of a CP-RA to a large number of angles because of the increased mismatching and scanning loss. In addition, most of the CP-RAs presented in the literature have been designed for a single beam and the beam-scanning characteristics have been rarely investigated. For simplicity, a mechanical beam scanning technique is adopted in this letter, as shown in Fig. 9(a). The position (phase center) of the RHCP horn antenna is mechanically rotated (displaced) along the focal arc of the CP-RA in the scanning plane (*yz* plane) in front of the CP-RA with scanning angles (θ_{scan}) from −35° to +35° increased in steps of 5°, and the scanned collimated RHCP beams are investigated carefully. The beam-scanning characteristics of the proposed CP-RA are presented in Fig. 9(b)–(d). As can be seen, for the proposed CP-RA, the main RHCP beam can be steered by 70° ($\theta_{\text{scan}} = 0°, \pm5°, \pm10°, \pm15°, \pm20°, \pm25°, \pm30°, \pm35°$). The gain loss within the scanning range is about 3 dB and the beam squint is from 0° to 1.3°. The gains of the scanned beams are decreased compared to the main beam in the boresight direction and this can be attributed to the increased phase error across the CP-RA aperture. A comparison between the radiation performances of the CP-RA proposed in this letter and other previously published works in the literature is given in Table I. As a result of the combination of an efficient PB meta-atom, geometric phase, and subwavelength periodicity, Table I shows that the proposed CP-RA has a better radiation characteristics in terms of gain BW, AR, beam-scanning capabilities, and efficiency. To further improve the beam-scanning characteristics, other phase distributions such as bifocal phase distribution [35], four focuses [36], parabolic cylindrical phase [37], or spherical phase distribution in [38] can be used instead of the phase distribution used in this work (for simplicity). In addition, reduction of feed blockage in the boresight direction can also be achieved using feeding mechanisms other than center-fed.

TABLE I
Radiation Characteristics Comparison of This Work With Previously Published CP-RA

Ref.	[15]	[25]	[18]	[33]	[34]	This Work
Feed Polarization	LP	LP	CP	CP	LP	CP
Unit cell size	0.33λ	0.21λ	0.3λ	0.53λ	0.62λ	0.28λ
Thickness	-	0.16λ	0.1λ	0.1λ	-	0.12λ
No. of metallic layers	1	2	1	1	1	1
No. of dielectric layers	1	3	1	1	1	1
gain BW 1-dB	17%	-	19.1%	11.1%	-	24.5%
gain BW 3-dB	30%	40%	-	-	7.6%	46.15%
AR BW 3-dB	11%	40%	40%	20.3%	8.6%	46.15%
Peak AE	39%	40%	50%	37.1%	21.8%	49.93%
PB Phase	No	No	No	Yes	No	Yes
Beam scanning	No	Yes	No	No	No	Yes
Scanning angle	No	±45	No	No	No	±35

V. Conclusion

In summary, it has been shown that the combination of the subwavelength periodicity and geometrical rotation phase can improve the focusing and beam-scanning characteristics of a CP-RA. The proposed CP-RA has an ultrathin thickness (0.11λ_o) and subwavelength periodicity (0.28λ_o). Both simulation and experimental results show that the proposed CP-RA can provide a 1 dB gain BW of 24.5%, 3 dB gain BW of 46.15%, peak AE of 49.93%, 3 dB AR of 46.15%. Furthermore, a beam scanning with 70° (±35°) scanning angle is achieved with gain scanning loss of less than 3 dB and beam squint of less than 1.3° within the whole frequency band.

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