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Gain Enhanced Circularly Polarized Antenna With RCS Reduction Based on Metasurface

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ABSTRACT In this paper, a gain-enhanced circularly polarized (CP) patch antenna with in-band and out-of-band radar cross section (RCS) reduction is designed, fabricated, and analyzed. Both the proposed and reference CP patch antennas are etched with truncated corners and designed to operate at 8.2 GHz, while the proposed antenna is surrounded by chessboard arrangement of an ultra-wideband and high-efficiency polarizer that can rotate linearly polarized incident waves into the orthogonal one ranging from 7.55 to 20.74 GHz. Meanwhile, the polarization conversion ratio remains higher than 0.9 within the operating band. The simulation results show that the realized gain of the proposed antenna is enhanced by 2.5 dB at 8.2 GHz, and 11 dB average RCS reduction is achieved within the operating band (7.55–20.74 GHz). The working mechanism of the simultaneous realization of gain enhancement and RCS reduction is analyzed in detail. Finally, the designed and reference antennas are fabricated and tested, which demonstrates the effectiveness of the proposed design method. The proposed antenna can be potentially applied in a future communication device and stealth platform.

INDEX TERMS Circularly polarized antenna, gain enhancement, polarization rotation reflective metasurface, RCS reduction.

I. INTRODUCTION

In order to meet the requirement of defense electronic technology, extensive research has been carried out in radar cross section (RCS) reduction. Antennas are the device receiving and transmitting electromagnetic waves, which contribute greatly to the whole RCS of the low observable platform. Therefore, the design of antennas with RCS reduction is of great emphasis for defense applications. In recent years, various approaches have been adopted in literature to reduce RCS of antennas, such as shaping the radiation part [1], using radar absorbing material [2], and applying a frequency selective surface [3]. The combination of two artificial magnetic conductors (AMCs) can also be used for broadband RCS reduction based on phase cancellation [4]. Most of the reported RCS reduction methods are introduced to linearly polarized (LP) antennas. More attention should be paid to low RCS realization of circularly polarized (CP) antennas [5], [6], which have been widely used in wireless and communication systems. Besides, RCS reduction of antennas often results in the deterioration of the radiation performance, especially for in-band RCS reduction. So, it is important to keep or improve the antenna radiation performance in the processing of a low RCS design. Up to now, very few papers achieving the design of gain enhanced CP antennas with in-band and out-of-band RCS-reduction have been reported, which is urgently required by a communication device and low observable platforms.

Metamaterial [7] is an artificial material with the properties that haven't been found in naturally occurring materials, which has been increasingly applied in the design of the antenna with excellent performance [8]–[10]. The polarization rotation reflective metasurface (PRRM) is a kind of metamaterial that can manipulate the polarization state of reflected waves [11]–[13]. In [14]–[19], PRRMs were used for antenna RCS reduction. Significant in-band and out-of-band RCS reduction of the microstrip antenna was observed [14]. In [15], a fishbone-shaped metasurface chessboard array was used as the coating layer of a slot array antenna, which obtained 5dB RCS reduction in a wide band ranging from 6 to 18GHz. Gain enhancement and In-band RCS reduction were achieved for a dual-band antenna based on PRRM in [16]. A low-RCS and high-gain antenna composed of the Fabry-Perot cavity and chessboard metasurface was proposed in [17]. And the combination of Fabry-Perot cavity and chessboard polarization conversion metasurface was used for the design of high-gain CP antenna with low-RCS [18]. In [19], PRRM was used as the radiator of the CP antenna. To achieve RCS reduction, three other artificial magnetic conductors were intended to obtain the discrepancies among the PRRM.

In this paper, a gain enhanced and low-RCS circularly polarized patch antenna based on chessboard-type polarization rotation reflective metasurface is designed and verified. The proposed PRRM can achieve linear polarization rotation in an ultra-wideband frequency range, which corresponds to the monostatic RCS reduction frequency band. A rectangular patch with truncated corners is designed and used as the radiator of the reference and proposed CP antenna. After loading the proposed chessboard-type PRRM around the circularly polarized radiator, gain enhancement is realized by strong coupling between radiation structure and the surrounding metasurface structure. RCS reduction is achieved by the destructive interference of the waves reflected from different metasurface sub-arrays. The advantages of the proposed work include: low profile, gain enhancement, and ultra-wideband RCS reduction of a CP antenna. The proposed approach is verified through measurement, and it has a good consistency with the simulated results.

II. DESIGN OF THE PROPOSED ANTENNA

A. DESIGN OF THE PROPOSED PRRM

The schematic diagram and geometric parameters of the basic unit cell of the proposed PRRM are illustrated in Fig.1. All parameters of the unit cell are provided in Table 1. The unit cell is comprised of a top metallic layer and bottom ground

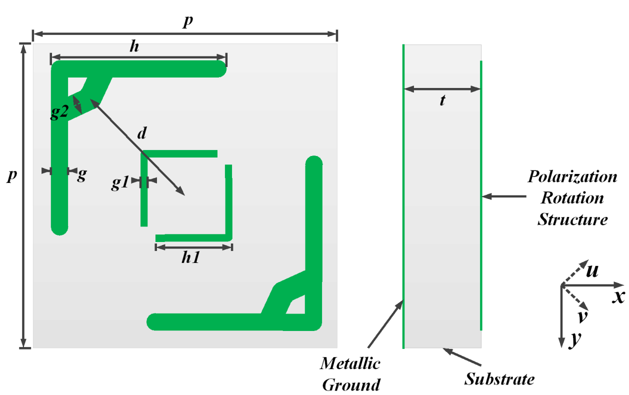

FIGURE 1. The schematic diagram and geometric parameters of the proposed metasurface unit cell.

TABLE 1. Optimized parameters of the proposed metasurface unit cell. (Unit: mm).

h	h1	d	p
5.2	2.4	4.5	10
g	g1	g2	d
0.57	0.24	0.75	3

planes with a dielectric substrate between them. The top layer is the polarization rotation structure that consists of two pairs of etched quasi-L-shaped patterns. Commercially available F4B substrate (relative permittivity of 2.65) with a thickness of 3mm is utilized as the dielectric layer. To ensure that the PRRM has an identical polarization rotation characteristic with x- or y-polarized normally incident wave, the top layer is designed to be symmetrical with respect to the u- and v- direction. The unit cell has been simulated in Ansys HFSS 15.0 using Mater/Slaver boundary conditions. The reflected phase difference and amplitude with u- and v-polarized incident waves are illustrated in Fig.2, where the reflection amplitude of u-polarized incidence is approximately equal to that of the incident wave with polarization along the v-direction. Moreover, the relative reflection phase difference ($\Delta\Phi$) between u- and v-polarized incidence is nearly $\pm 180^\circ$ from 7.55 to 20.74GHz. So, the proposed PRRM offers the opportunity to achieve polarization rotation in an ultra-wideband frequency range [12].

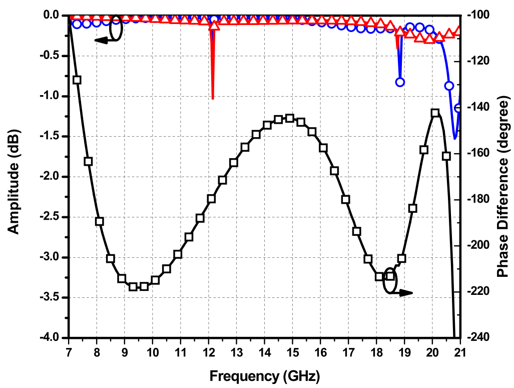

FIGURE 2. Simulated reflected phase difference and amplitude with the incident wave electric field along the u-axis and v-axis, respectively.

PCR is the figure-of-merit for the polarization rotation performance of the electromagnetic wave that can be expressed as $PCR = |R_{cross}|^2/(|R_{cross}|^2 + |R_{co}|^2)$ [20], where R_{co} and R_{cross} are the co- and cross-polarization reflection, respectively. The decomposition of the x-polarized incident electric field is depicted in Fig.3. Owing to the existence of metal ground, a perfect reflection is obtained. Under the assumption

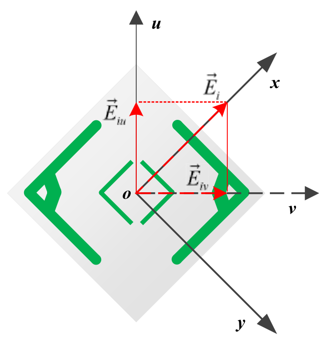

FIGURE 3. Decomposition of the of incident electric field.

that the amplitude of the incidence is 1, the incident wave can be expressed as $\vec{E}_i = \vec{E}_{iu} + \vec{E}_{iv} = \left(\sqrt{2}/2\right) \cdot (\vec{u} + \vec{v})$. The reflected coefficients in u- and v-direction are different owing to the anisotropic metasurface. Based on the assumption that the reflected coefficient in u-direction $\tilde{r}_u$ is 1, the anisotropy is represented in $\tilde{r}_v$. And $\tilde{r}_v$ can be written as

$$\tilde{r}_v = 1 \cdot e^{j\Delta\Phi} = \cos(\Delta\Phi) + j\sin(\Delta\Phi) \quad (1)$$

Therefore, the reflected wave can be expressed as

$$\vec{E}_r = \vec{E}_{ru} + \vec{E}_{rv} = \sqrt{2}/2\left(\vec{u} + e^{j\Delta\Phi} \cdot \vec{v}\right) \quad (2)$$

$|R_{cross}|^2$ is the absolute value of the projection of $\vec{E}_r$ on the y-direction. And $|R_{cross}|^2$ can be written as

$$|R_{cross}|^2 = \frac{1 - e^{j\Delta\Phi}}{2} \quad (3)$$

So, the relationship between PCR and phase difference $(\Delta\Phi)$ is

$$PCR = \frac{|R_{cross}|^2}{\left(|R_{cross}|^2 + |R_{co}|^2\right)} = \frac{1 - e^{j\Delta\Phi}}{2} \quad (4)$$

The curve of PCR as a function of phase difference $(\Delta\Phi)$ is plotted in Fig.4. It is worth mentioning that to ensure PCR greater than 0.9, $\Delta\Phi$ should be in the range of $180° \pm 36°$. The simulated $|R_{co}|$ and $|R_{cross}|$ of the proposed PRRM under the incident wave electric field along the x- or y-axis are shown in Fig.5 (a). It is observed that $|R_{co}|$ is under -10dB from 7.55 to 20.74GHz. There are five dips at 8.05, 12.0, 16.9, 19.45 and 20.6GHz where the incident waves are completely converted to the orthogonal ones. As depicted in Fig.5 (b), the bandwidth of PCR higher than 0.9 is up to 93.2%. At the five resonance frequencies, PCRs are above 98.6%. Since the proposed polarization rotation structure is a combination of different sized quasi-L-shaped resonators that have multiple resonance characteristics [21], the polarization rotator can thus work in ultra-wideband.

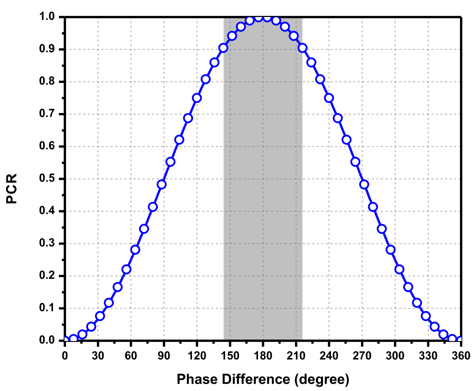

FIGURE 4. PCR as a function of $\Delta\Phi$.

B. ANTENNA CONFIGURATION

Chessboard-type arrangement of PRRM sub-array and its mirror sub-array has been demonstrated to realize RCS reduction [20]. Therefore, RCS of the chessboard configuration of the proposed PRRM [see Fig.6 (a)] is simulated and tested. The photograph of the manufactured chessboard structure is depicted in the inset of Fig.6 (b). The monostatic RCS reduction for normal incidence has been depicted in Fig.6 (b). Compared with the RCS of a metallic plate with the same size, the proposed chessboard configuration can realize noticeable RCS reduction as much as 10dB in an ultra-wide frequency band ranging from 7.5 to 20.4GHz. At the resonance frequency of 8.2GHz, the RCS reduction value is higher than 20dB. The measurement is performed in the frequency range lower than 18GHz due to the limitation of the test environment. Considering fabrication and measurement errors, acceptable agreement between the measured and simulated results is achieved.

A traditional circular polarization microstrip antenna working at 8.2GHz, which is printed on the same substrate with the PRRM, is designed as reference one. The proposed antenna is designed by surrounding the radiation patch with the chessboard configuration metasurface. The geometry and parameters of the proposed antenna are depicted in Fig.7.

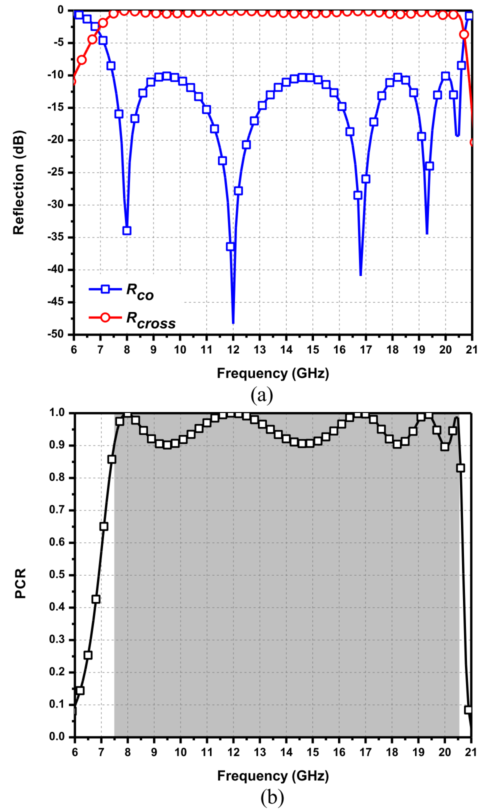

FIGURE 5. (a) Simulated co- and cross-polarization reflection and (b) PCR of the proposed PRRM.

III. RADIATION ANG SCATTERING PERFORMANCES

A. RADIATION PERFORMANCE

The prototypes of the proposed and reference antennas are fabricated and tested. The photographs of two prototypes are

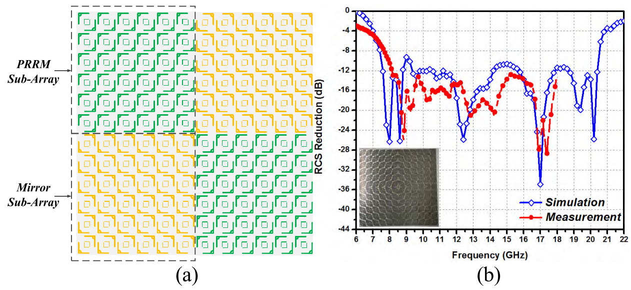

FIGURE 6. (a) Chessboard configuration of the proposed PRRM. (b) RCS reduction of the chessboard configuration compared with the reference metallic plate.

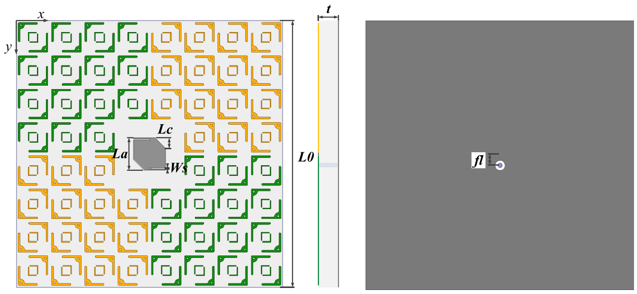

FIGURE 7. The geometry of the proposed antenna. Dimensions of the proposed antenna are L0 = 80mm, La = 9.7mm, Lc = 3.2mm, Ws = 0.4mm, and t = 3mm, fl = 3mm.

shown in Fig.8. It is critical to preserve the radiation properties during the low-RCS antenna design process. So, we first discuss the radiation performance of the designed antenna. The resonance frequency and impedance bandwidth of the designed antenna coincide well with the reference one, which is indicated in Fig.9 (a). The resonance frequency of the two antennas is 8.2GHz. Fig.9 (b) presents the comparison of the axial ratio of the two antennas. It is clearly observed that the axial ratio bandwidth (axial ratio < 3dB) of the designed antenna is wider than the reference one. Fig.10 reports the simulated left-hand circularly polarized (LHCP) and right-hand circularly polarized (RHCP) radiation patterns of both antennas at 8.2GHz. Fig.11 gives the measured radiation patterns of the two antennas. By comparing the variation of the realized boresight RHCP gain level with respect to the reference results, it is apparent that maximum gain increases to 8.8dBi, that is, 2.5dB higher than the original one. Acceptable consistency between the simulation and measurement results is achieved, which approves that the presence of the proposed metasurface can improve the radiation performance. The slight discrepancies are explained by the measurement and fabrication tolerance.

To investigate the physical mechanism of gain enhancement, the current distribution of the reference and proposed antenna at 8.2GHz is provided in Fig.12. In radiation case, the proposed metasurface structure acts as parasitical radiator due to the strong coupling between the radiation patch and metasurface. By comparing the magnitude of surface current as shown in Fig.12 (a) and Fig.12 (b), it can be seen

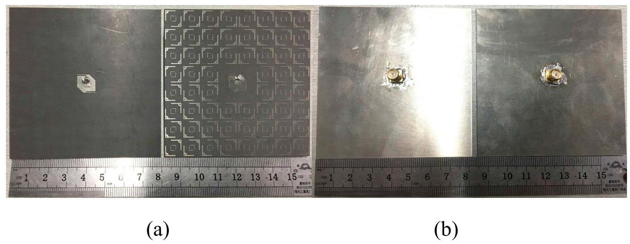

FIGURE 8. Photographs of the reference and proposed antennas: (a) top view, (b) bottom view.

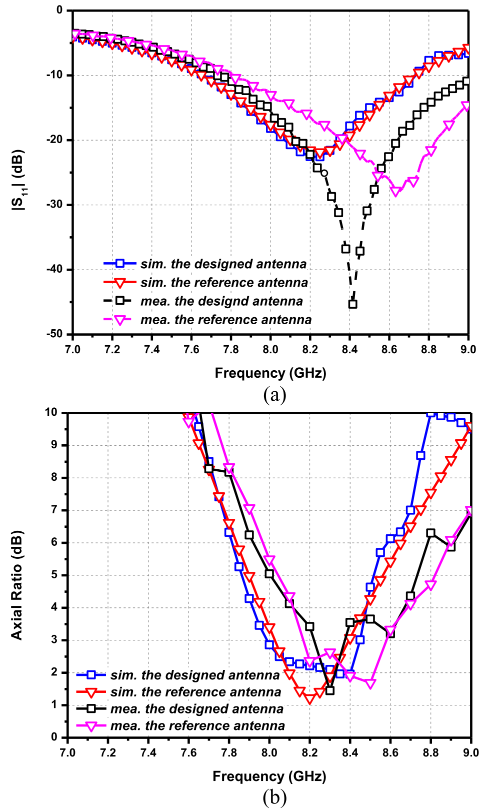

FIGURE 9. Comparison of (a) S-parameters and (b) Axial Ratio between the two antennas.

intuitively that the radiation aperture is enlarged after equipping metasurface structures. Moreover, the surface current vector distribution of the proposed antenna at 8.2GHz is depicted in Fig.12 (c) and Fig.12 (d). It can be clearly observed that two orthogonal modes with 90° phase difference are excited to achieve right-hand circularly polarized radiation. Hence, the arrangement of the metasurface structure is proved to be able to produce circular polarization radiation. Therefore, the improvement of radiation aperture and the layout of the metasurface structure is the key reasons for the gain enhancement.

B. SCATTERING PERFORMANCE

To verify the ultra-wideband RCS reduction characteristic of the proposed antenna, the RCS for normal incidence of both antennas is simulated and measured. The monostatic RCS of

TABLE 2. Comparison with the antennas with RCS reduction based on metasurfaces.

	Size	Polarization state	Gain variation	In-band RCS reduction	Average RCS reduction	RCS reduction bandwidth
[5]	$2.67\times2.67\times0.05\lambda^3$	CP	/	~ 6dB	> 6dB	4.53-6.7GHz (38.6%)
[6]	$2.675\times2.675\times0.596\lambda^3$	CP	+3.2dB	4dB	NG	4-13GHz (105.88%)
[9]	$2.256\times2.256\times0.056\lambda^3$	LP	+3dB	NG	6dB	4.35-7.8GHz (56.8%)
[10]	$3.39\times3.39\times0.0433\lambda^3$	LP	+2.5dB	NG	>4.3dB	2.85-3.95GHz (32%)
[17]	$0.6\times0.6\times0.2472\lambda^3$	CP	+1dB	/	10.68dB	9-17GHz (61.54%)
[18]	$1.98\times1.98\times0.4057\lambda^3$	CP	+3dB	NG	NG	6-14GHz (80%)
[19]	$1.23\times1.23\times0.067\lambda^3$	CP	/	NG	> 6dB	5-10GHz (66.67%)
Proposed	$2.18\times2.18\times0.082\lambda^3$	CP	+2.5dB	11.5dB	11dB	7.55-20.75GHz (93.25%)

LP: Linear polarization.
CP: Circular polarization.

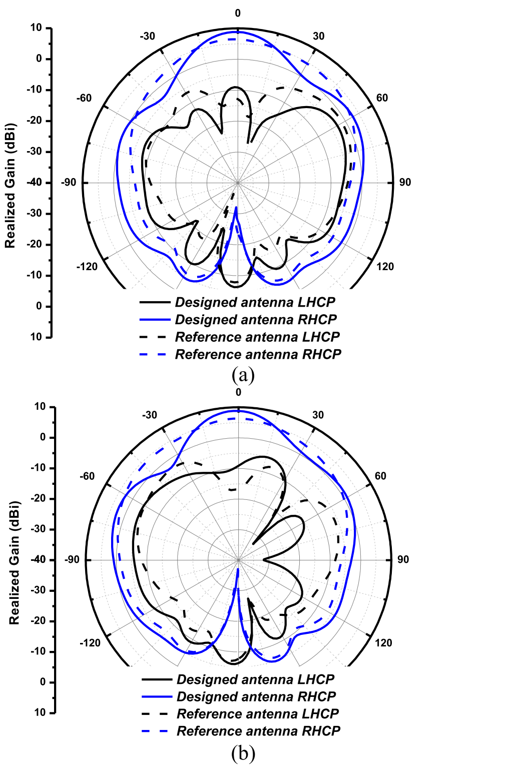

FIGURE 10. Simulated radiation patterns of the two antennas at 8.2GHz. (a) yoz- and (b) xoz-planes.

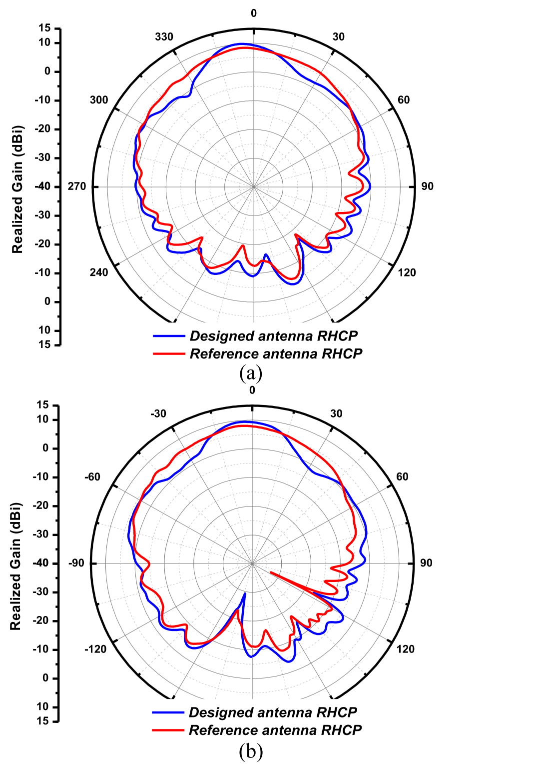

FIGURE 11. Measured radiation patterns of the two antennas at 8.2GHz. (a) yoz- and (b) xoz-planes.

designed and reference antennas are plotted in Fig.13. Compared with the reference one, the proposed antenna can realize noticeable RCS reduction ranging from 7.55 to 20.74GHz, covering the working band of the proposed antenna. The average RCS reduction value is larger than 11dB during thewhole band for both polarizations. Moreover, the in-band RCS reduction value as much as 11.5dB is achieved.

The monostatic RCS performance at the working frequency under oblique incidence is reported in Fig.14. It can be observed that in-band RCS reduction is achieved over a certain angular range. Fig.15 shows the simulated 3D bistatic scattered field of both antennas at 10GHz. Under normal illumination with y-polarization, the scattered energy near the z-axis is significantly reduced. The energy is redirected to four grating lobs $(\theta, \varphi) = (-22°, 45°)$, $(22°, 45°)$, $(-22°, 135°)$, $(22°, 135°)$.

Table 2 presents a comparison of gain variation and RCS reduction among the proposed work and other reported low RCS antennas based on metasurfaces. It can be seen that the gain enhancement of [6] and [18] is slightly larger than that of the proposed work, while a much higher profile is needed in [6] and [18] resulting from the fabry-perot cavity structure required for gain enhancement. So the proposed work can achieve equally level radiation improvement with lower profile. In [6], the designed CP antenna achieves the RCS reduction within a frequency band of 105.8%, while the

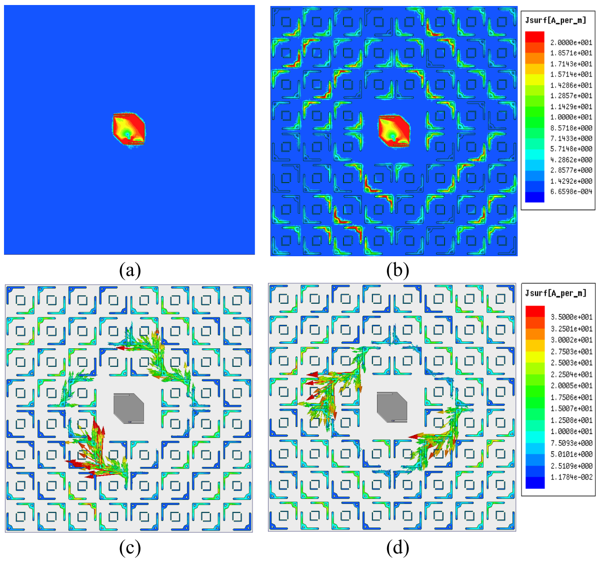

FIGURE 12. Simulated current distribution of (a) reference antenna, and (b) proposed antenna. The surface current vector distribution of the proposed antenna in radiation case (c) at 8.2GHz phase = 0° and (d) at 8.2GHz phase = 90°.

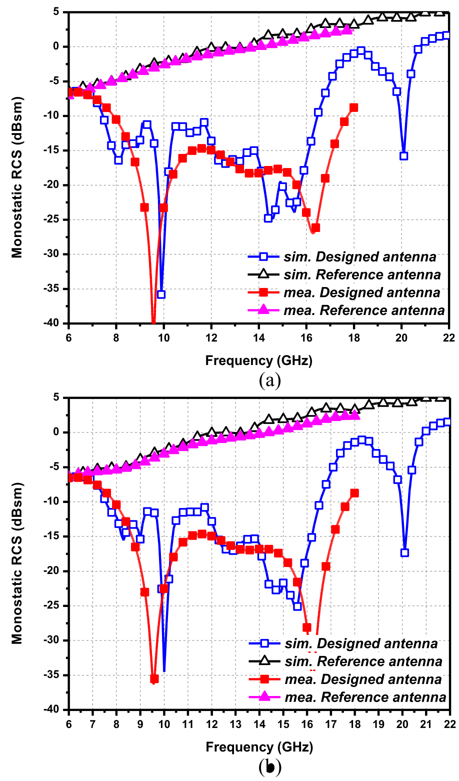

FIGURE 13. Simulated and measured RCS of both antennas for normal incidence with the electric field parallel to (a) x- and (b) y-axis.

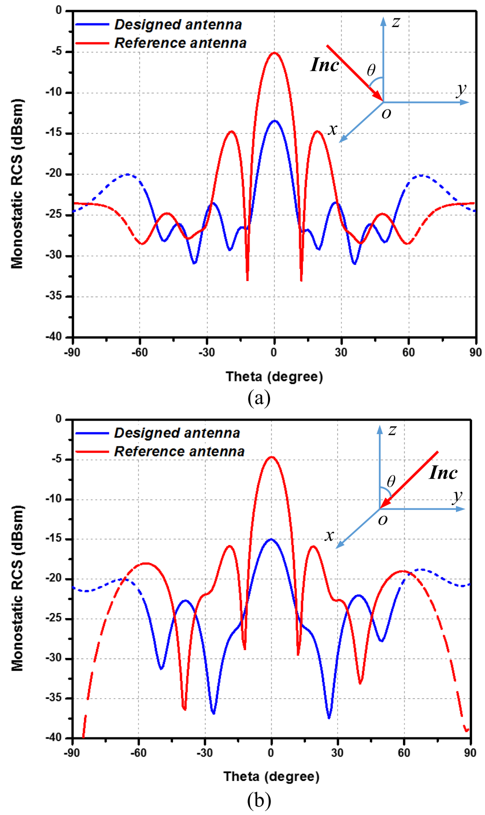

FIGURE 14. Comparison of the monostatic RCS as a function of incident angle for (a) x- and (b) y-polarization waves at 8.2GHz.

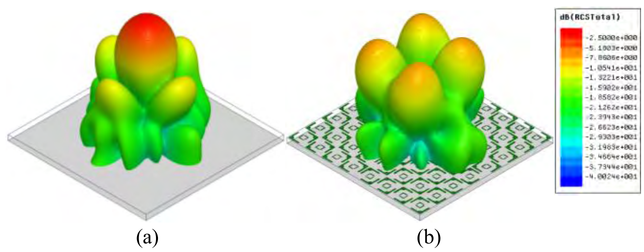

FIGURE 15. 3D bistatic scattered field at 10GHz under normal incidence with y-polarization for (a) reference antenna and (b) designed antenna.

in-band RCS reduction value is only higher than 4dB. The RCS reduction level (10dB) of [18] is the same as that in this work. However, the polarization conversion properties of the proposed work is better than that of [18]. As a result, the RCS reduction bandwidth of this work reaches 93.25%. Compared with the low RCS antennas in [5] and [17], the proposed work obtains wider RCS reduction bandwidth with larger reduction value. Besides, gain enhancement and in-band RCS reduction are achieved simultaneously in the proposed work. The aperture efficiency improvement is the key reason for gain enhancement in [9] and [10], which is identical with the method used in this work. However, the proposed work is designed for CP radiation and obtains a larger RCS reduction value within wider frequency bandwidth. In [19], a comprehensive design of low RCS CP antenna was proposed by using three kinds of AMCs. But the integrated design method cannot be used in the conventional antenna with a desired performance. Compared with the other antennas in the open literatures, the main contribution of the proposed work is simultaneous realization of gain enhancement and ultra-wideband RCS reduction by directly surrounding the circular polarization antenna with chessboard-type metasurface.

IV. CONCLUSION

A novel CP antenna with gain enhancement and RCS reduction performance based on PRRM is simulated and measured in this paper. The proposed PRRM can achieve ultra-wideband polarization rotation from 7.55 to 20.74GHz with PCR higher than 90%. The numerical simulations and experimental measurements show that the radiation and scattering performance of the proposed antenna is improved with the incorporation of the polarization rotation reflector. Compared with the reference antenna, maximum gain of the proposed antenna is enhanced by 2.5dB within the operating band, and 11dB average RCS reduction is achieved from 7.55 to 20.74GHz. This proposed antenna can be used in a future communication device and low observable platform.

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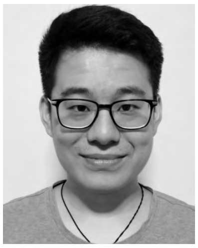

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