Manipulation of Terahertz Wave Using Coding Pancharatnam–Berry Phase Metasurface

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Abstract: Coding metasurface offers a promising way for manipulating electromagnetic waves using several structural metaparticles or changing the metaparticle geometry parameters. It leads to time-consuming optimization in multibit coding designs. Different from the previous conventional coding metasurface, both Pancharatnam–Berry (PB) phase and the predesigned coding sequences in the coding elements are used to manipulate terahertz wave, which becomes more flexible. In this paper, a multibit digital coding metasurface is constructed using the PB phase based on a same size metaparticle with various orientations. Both theoretically calculated and numerically simulated scattering patterns of the designed coding PB phase metasurfaces demonstrate the expected manipulations. The designed coding metasurfaces having polarization dependence for left circularly, right circularly, and linearly polarized waves are confirmed. The maximum bandwidth of a radar cross section reduction of approaching –10 B is 0.8 THz (range from 0.8 to 1.6 THz).

Index Terms: Terahertz wave, Pancharatnam-Berry phase, multi-bit coding metasurfaces.

1. Introduction

Metasurface is a typical of two-dimensional ultra-thin metamaterial, which occupies less physical space, avoid large transmission losses, and is easy to manufacture. It allows polarization regulation and wave front manipulation at sub-wavelength scales and exhibits some special physical phenomena, such as high-efficiency polarization conversion [1]–[4], anomalous reflection and refraction [5]–[8], focus impinge waves [9], [10], vortex beam [11], quarter-wave plate [12], [13], highly efficient beam steering [14] and hologram [15]. In 2014, Cui et al. [16] proposed the concept of the coding metasurface, which can manipulate microwave wave from 8.1 GHz to 12.7 GHz by binary coding elements, where the digital bits “0” and “1” was used to present unit cells which have the reflection phase responses of 0° and 180°, respectively. In 2017, H. Xu, et al. [17] designed a bifunctional metasurfaces to control electromagnetic waves. More recently, some coding metasurface structures are utilized to manipulating terahertz wave and realized the radar cross section (RCS) reduction [18]–[20]. However, the above mentioned coding metasurfaces with different reflection phase responses are obtained involving several meta-particles with different geometrical...
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Fig. 1. Design of the proposed unit cell. (a) Three-dimensional schematic of the unit cell. Reflection magnitude of the unit cell under normal incidence of the LCP (b) and RCP (c) waves. Here, \( r_{LL} \) and \( r_{RR} \) are the reflection magnitude of the co-polarization and cross-polarization under vertical radiation of the LCP (RCP) waves, respectively. (d) Reflection phase and magnitude value under normal incidence of the x and y-polarized waves.

structures, which require a complex and time-consuming optimization processing in multi-bits coding designs. The Pancharatnam-Berry (PB) phase [21]–[23] can overcome the shortcoming and acquire multi-bits coding by rotating the metal-particles without changing the meta-particles size.

In our work, we used PB phase metasurface with coding elements to manipulate terahertz wave not only the predesigned coding sequences but also the different reflection phase of coding elements. To generate these PB phase metasurfaces, we utilize the two-eye-shaped meta-particle [24] as the unit cell which has polarization dependent characteristic under normal incidence of the left circularly polarized plane (LCP), right circularly polarized plane (RCP) and linearly polarized (LP) waves. Based on PB phase, we generate the coding elements for 1 bit, 2 bit and multi-bit coding metasurfaces. Both theoretic analysis and numerical simulation indicate that our presented coding PB phase metasurfaces have strong suppressed backward scattering and low RCS in a wide frequency band due to the disorder phase distribution of the coding metasurfaces. Compared with the previous work [18], the presented PB phase coding metasurfaces have less time-consuming in simulation processing, polarization dependent, and a more flexible capability of controlling the terahertz wave.

2. Unit Cell Structure Design and Simulation

In this work, as depicted in Fig. 1(a), the meta-particle is composed of the two-eye-shaped metallic pattern, dielectric substrate with permittivity \( \varepsilon = 3.0 \) and loss tangent \( \tan \delta = 0.03 \), and metallic ground plate. The period of the unit cell is \( P = 60 \, \mu m \) and the thickness of dielectric substrate layer is \( H = 30 \, \mu m \). Both the metallic pattern and metal ground plate are made of copper with a conductivity of \( 5.8 \times 10^7 \, S/m \) and a thickness of \( 0.2 \, \mu m \). The geometrical parameters of metallic pattern are \( L = 50 \, \mu m \), \( W = 14 \, \mu m \), \( R_1 = 25 \, \mu m \), \( R_2 = 20 \, \mu m \) and \( R_3 = 15 \, \mu m \).

The reflection magnitude of the co-polarization and cross-polarization under normal incidence of the LCP and RCP waves has been calculated using Commercial software CST Microwave Studio, as shown in Fig. 1. Fig. 1(b) and (c) give the simulated reflection magnitudes in the frequency from 0.6 THz to 2 THz under normal incidence of the LCP and RCP waves, respectively. From the figures,
Fig. 2. Surface current distribution for top metallic pattern, ground metal plane under LCP polarization. (a), (b) and (c) are surface current distribution for top metallic pattern at 0.89 THz, 1.1 THz and 1.57 THz, respectively. (d), (e) and (f) are surface current distribution for ground metal plane at 0.89 THz, 1.1 THz and 1.57 THz, respectively.

Fig. 3. Surface current distribution for top metallic pattern, ground metal plane under RCP polarization. (a), (b) and (c) Surface current distribution for upper metal pattern at 0.89 THz, 1.1 THz and 1.57 THz, respectively. (d), (e) and (f) Surface current distribution for ground metal plane at 0.89 THz, 1.1 THz and 1.57 THz, respectively.

one can see that the reflected wave is mainly RCP (LCP) wave under normal incidence of the LCP (RCP) waves. Since the metal ground plate reflects the circularly polarized (CP) normal incidence wave and inverts the polarization state of incident CP wave. In addition, it can be noted that there are three resonance frequencies at 0.89 THz, 1.1 THz and 1.57 THz under normal incidence of the LCP, RCP and LP waves. The wide bandwidth of the meta-atom is due to the multiple resonant modes. Fig. 1(d) shows the phase and magnitude values under normal incidence of the x- and y-polarized waves. From the figure, one can see that a $\pi$ phase difference between the $x$- and $y$-polarized waves achieves in the frequency range from 0.8 THz to 1.6 THz.

The surface current distribution on the top metallic pattern and the ground metal plane of the three resonances have been simulated, as shown in Fig. 2 and Fig. 3, respectively. Fig. 2(a)–(c) represent for the current distribution of the top metallic pattern at 0.89 THz, 1.1 THz and 1.57 THz under normal incidence of the LCP wave, respectively. Fig. 2(d)–(f) show the current distribution of the ground metal plane at 0.89 THz, 1.1 THz and 1.57 THz under normal incidence of the LCP wave, respectively. Similarly, Fig. 3(a)–(c) depict the current distribution of the top metallic pattern...
at 0.89 THz, 1.1 THz and 1.57 THz under vertical incidence of the RCP wave and Fig. 3(d)–(f) serve as the current distribution of the ground metal plane at 0.89 THz, 1.1 THz and 1.57 THz under normal incidence of the RCP wave, respectively. According to the Fig. 2 and 3, one can see that the surface current distribution of the top metallic pattern is not uniform. The surface current is counterbalanced along x-axis orientation and concentrated along y-axis orientation. So the top metallic pattern services as a dipole in y-orientation and causes the phase change different in x-axis and y-axis directions. One sees that there is 90° phase delay between x- and y- orientations since a CP wave can be decomposed into two LP waves. Obviously, an inverse phase delay is generated between x-axis and y-axis directions under normal incidence of the CP wave. According to the Fig. 2 and 3, one can see that the current directions of top metallic pattern and the ground metal plane under normal incidence of the LCP and RCP waves are opposite at the same resonant frequency of 0.89 THz, 1.1 THz and 1.57 THz. The anti-parallel current leads to the multiple electromagnetic resonant modes of the unit cell structure, which offers also a wide bandwidth property. Therefore, the proposed two-eye-shaped unit cell has the merit of wide bandwidth reflection phase manipulation.

Here, we use a PB phase metasurface with different phase combining with different pre-designed coding sequences to control the terahertz wave. For example, for 1-bit coding metasurfaces case, two unit cells with the inverse phase information are required. Similarly, for the 2-bit coding metasurfaces, the adjacent unit is required a fixed phase difference of 90° for four digital units. Actually, for a 3-bit coding metasurfaces case, eight digital unit cells with a fixed phase difference of 45° are employed to imitate the digital bits of "000", "001", "010", "011", "100", "101", "110" and "111". Based on the PB phase, we can rotate the top metallic pattern with different angle to obtain the basic unit cells. In detail, a ±2α reflection phase shift of the digital unit cell can be realized with a rotation angle α of the top metallic pattern, where “+” and “–” represent the LCP and RCP waves (see in the inset of Fig. 4(a)), respectively. Obviously, in order to obtain eight basic digital unit cells, the rotation angle α is changed from 0° to 157.5° with a step width of 22.5°. Fig. 4(b) and 4(c) depict the reflection magnitude and reflection phase for cross-polarization with different rotation angle α of the top metallic pattern under normal incidence of the LCP wave. From the figure, it can be noted that the eight basic unit cells have the same reflection magnitude which is close to 1 dB in a wide frequency region from 0.8 THz to 1.6 THz. When the phase increases with 45° steps in the whole frequency range, the reflection magnitude and reflection phase shift of the basic digital unit cells are insensitive for the incident angle. Fig. 4(d) gives the digital elements of the 1-bit, 2-bit and 3-bit coding PB phase metasurfaces. Fig. 4(e) shows the effect of spatial rotation on the phase for linearly polarized waves. In this paper, we employed 4 × 4 basic unit cells as digital elements (named super unit cells) in order to minimize the couple effect of the unit cells. The periodicity of the super units along x and y direction for metasurfaces 1, 2, 3 are 4 × 60 μm.

3. Design and Simulation of Coding Metasurfaces

We know that different physical phenomena of the scattering field pattern are produced by an arbitrary coding metasurface which has the unique coding sequence. The desired scattering field pattern can be realized using the coding metasurface with pre-designed coding sequence. Here, three kinds of regular coding metasurfaces are used to verify the property that 3-bit regular coding metasurfaces can redirect terahertz wave to arbitrary direction along the far-field scattering patterns. The polarization dependent are calculated by using the commercial software CST under normal incidence of the LCP, RCP and LP waves at the frequency of 1.0 THz. Fig. 5(a)–(c) and Fig. 6(a)–(c) show the results for the coding metasurface 1 direction under normal incidence of the LCP, RCP, and LP waves at 1.0 THz. Fig. 5(d)–(f) and Fig. 6(d)–(f) depict the coding metasurface 2. Fig. 5(g)–(i) and Fig. 6(g)–(i) give the coding PB phase metasurface 3. The simulated 3D and 2D far field scattering patterns are shown in Fig. 5 and 6, respectively. In Fig. 5(a) and Fig. 6(a), it is observed that the normal incidence of the LCP wave is reflected into the main lobe direction of the primary pattern with (θ = 9°, ϕ = 0°). However, when the normal incidence wave is RCP, the azimuth angle ϕ increases from 0° to 180° while the elevation angle is still θ = 9°, as depicted in Fig. 5(b) and Fig. 6(b). It is because LCP wave has a positive 45° phase gradient difference in x-axis direction
while RCP wave has a negative 45° phase gradient difference. That is to say, the LCP and RCP waves have an opposite phase gradient difference on the coding PB phase metasurfaces in the x-axis. As shown in Fig. 5(c) and Fig. 6(c), it is found that the normal incidence LP wave is reflected into two symmetric directions with the angle of ($\theta_1 = \arcsin(\lambda / \Gamma_1) = 9^\circ$, $\varphi = 0^\circ$ or $\varphi = 180^\circ$). Since the LP wave can be decomposed as a LCP and a RCP wave, where $\lambda$ is the wavelength of 1.0 THz, $\Gamma_1$ represents the physical length of one period metasurface 1 of the gradient phase distribution, and $\Gamma_1 = 8 \times 240 \mu$m. As illustrated in Fig. 5(d) and Fig. 6(d), the normal incidence LCP wave is reflected into two symmetrical orientations with the angle of ($\theta_2 = 38.7^\circ$, $\varphi = 76^\circ$) and ($\theta_2 = 38.7^\circ$, $\varphi = 284^\circ$), where $\theta_2 = \arcsin(\lambda / \Gamma_2)$, $\Gamma_2$ represents the physical length of one period
Fig. 5. 3D far-field scattering patterns of 3-bit coding metasurface with “000, 001, 010, 011, 100, 101, 110, 111 . . . “ coding sequence in the x-axis direction [Named metasurface 1] under normal incidence of the LCP (a), RCP (b), LP (c) waves at 1.0 THz. 3D far-field scattering patterns of 3-bit coding metasurface with “000, 001, 010, 011, 100, 101, 110, 111/100, 101, 110, 111/000, 001, 010, 011 . . . “ coding sequence in the x-axis direction [Named metasurface 2] under normal incidence of the LCP (d), RCP (e), LP (f) waves at 1.0 THz. 3D far-field scattering patterns of 3-bit coding metasurface with “000, 001, 010, 011, 100, 101, 110, 111/000, 001, 010, 011, 100, 101, 110, 111, 000, 001, 010, 011 . . . “ coding sequence in the x-axis direction [Named metasurface 3] under normal incidence of the LCP (g), RCP (h), LP (i) waves at 1.0 THz.

Fig. 6. 2D far-field scattering of coding metasurface 1 under normal incidence of the LCP (a), RCP (b), LP (c) waves at 1.0 THz. 2D far-field scattering of coding metasurface 2 under normal incidence of the LCP (d), RCP (e), LP (f) at 1.0 THz. 2D far-field scattering of coding metasurface 3 under normal incidence of the LCP (g), RCP (h), LP (i) at 1.0 THz.
metasurface 2 of the gradient phase distribution, and $\Gamma_2 = 2 \times 240 \mu m$. But, for the RCP wave normal incidence, the angles of the reflected two symmetrical orientations become $(\theta_2 = 38.7^\circ, \varphi = 104^\circ)$ and $(\theta_2 = 38.7^\circ, \varphi = 256^\circ)$, as depicted in Fig. 5(e) and 6(e). For the LP wave, it is observed that the normal incident of the LP wave is reflected into four symmetrical orientations with the angle of $(\theta_2 = 38.7^\circ, \varphi = 76^\circ)$, $(\theta_2 = 38.7^\circ, \varphi = 104^\circ)$, $(\theta_2 = 38.7^\circ, \varphi = 256^\circ)$ and $(\theta_2 = 38.7^\circ, \varphi = 284^\circ)$, as shown in Fig. 5(f) and 6(f). For coding metasurface 3, as described Fig. 5(g) and Fig. 6(g), the LPC wave normal incidence is reflected to three orientations with angles of $(\theta_1 = 9^\circ, \varphi = 0^\circ)$, $(\theta_3 = 24.6^\circ, \varphi = 69.4^\circ)$ and $(\theta_3 = 24.6^\circ, \varphi = 290.6^\circ)$. Likewise, the reflected angles of the RCP wave normal incidence become $(\theta_2 = 9^\circ, \varphi = 180^\circ)$, $(\theta_2 = 24.6^\circ, \varphi = 110.6^\circ)$ and $(\theta_2 = 24.6^\circ, \varphi = 249.4^\circ)$ where $\theta_2 = \arcsin(\lambda/\Gamma_2)$, $\Gamma_3$ represents the physical length of one period metasurface 3 of the gradient phase distribution, and $\Gamma_3 = 3 \times 240$ um, as depicted in Fig. 5(h) and 6(h). As shown in Fig. 5(i) and 6(i), it is found that the normal incidence LP wave is reflected into six symmetrical orientations with the angle of $(\theta_1 = 9^\circ, \varphi = 0^\circ)$, $(\theta_3 = 24.6^\circ, \varphi = 69.4^\circ)$, $(\theta_3 = 24.6^\circ, \varphi = 290.6^\circ)$, $(\theta_1 = 9^\circ, \varphi = 180^\circ)$, $(\theta_3 = 24.6^\circ, \varphi = 110.6^\circ)$ and $(\theta_3 = 24.6^\circ, \varphi = 249.4^\circ)$.

Using the coding metasurfaces to control the terahertz far-field scattering pattern is not only decided by the coding sequences but also dependent on the incident polarization. Fig. 7(a)–(c) and Fig. 8(a)–(c) show the results for the coding metasurface 4 under normal incidence of the LCP, RCP, and LP waves at 1.0 THz. Fig. 7(d)–(f) and Fig. 8(d)–(f) depict the coding metasurface 5. Fig. 7(g)–(i) and Fig. 8(g)–(i) give the coding metasurface 6. In Fig. 7(a) and Fig. 8(a), it is noted that the normal incident LCP wave is reflected into the main lobe direction of the primary pattern with $(\theta = 9^\circ, \varphi = 90^\circ)$. When the normal incident wave is RCP, the azimuth angle $\varphi$ increases from $90^\circ$ to $270^\circ$ while the elevation angle is still $\theta = 9^\circ$, as depicted in Fig. 7(b) and Fig. 8(b). As illustrated in Fig. 7(c) and Fig. 8(c), it is also noted that the normal incidence LP wave is reflected into two symmetrical directions with the angle of $(\theta_1 = \arcsin(\lambda/\Gamma_1) = 9^\circ, \varphi = 90^\circ$ or $\varphi = 270^\circ)$. As shown in Fig. 7(d) and Fig. 8(d), the normal incidence LPC wave is reflected into two symmetrical orientations with the angle of $(\theta_2 = 38.7^\circ, \varphi = 14^\circ)$ and $(\theta_2 = 38.7^\circ, \varphi = 166^\circ)$. For the RCP wave normal incidence, the angles of the reflected two symmetrical directions become $(\theta_2 = 38.7^\circ, \varphi = 194^\circ)$ and $(\theta_2 = 38.7^\circ, \varphi = 346^\circ)$, as depicted in Fig. 7(e) and 8(e). For the LP wave, it is observed that the normal incident LP wave is reflected into four symmetrical orientations with
Fig. 8. 2D far-field scattering of coding metasurface 4 under normal incidence of the LCP (a), RCP (b), LP (c) waves at 1.0 THz. 2D far-field scattering of coding metasurface 5 under normal incidence of the LCP (d), RCP (e), LP (f) at 1.0 THz. 2D far-field scattering of coding metasurface 6 under normal incidence of the LCP (g), RCP (h), LP (i) at 1.0 THz.

the angle of \( \theta_2 = 38.7^\circ, \varphi = 14^\circ \), \( \theta_2 = 38.7^\circ, \varphi = 166^\circ \), \( \theta_2 = 38.7^\circ, \varphi = 194^\circ \) and \( \theta_2 = 38.7^\circ, \varphi = 346^\circ \), as shown in Fig. 7(f) and 8(f). For the metasurface 6, as described Fig. 7(g) and Fig. 8(g), the LCP wave normal incidence is reflected to three orientations with angles of \( \theta_1 = 9^\circ, \varphi = 90^\circ \), \( \theta_3 = 24.6^\circ, \varphi = 20.6^\circ \) and \( \theta_3 = 24.6^\circ, \varphi = 159.4^\circ \). Similarly, the reflected angles of the RCP wave normal incidence become \( \theta_1 = 9^\circ, \varphi = 270^\circ \), \( \theta_3 = 24.6^\circ, \varphi = 200.6^\circ \) and \( \theta_3 = 24.6^\circ, \varphi = 339.4^\circ \) where \( \theta_3 = (\lambda/\Gamma_3), \Gamma_3 = 240 \times 3 \text{ um} \), as depicted in Fig. 7(h) and 8(h). As shown in Fig. 7(i) and 8(i), it is indicated that the normal incidence LP wave is reflected into six symmetrical orientations with the angle of \( \theta_1 = 9^\circ, \varphi = 90^\circ \), \( \theta_3 = 24.6^\circ, \varphi = 20.6^\circ \), \( \theta_3 = 24.6^\circ, \varphi = 159.4^\circ \), \( \theta_1 = 9^\circ, \varphi = 270^\circ \), \( \theta_3 = 24.6^\circ, \varphi = 200.6^\circ \) and \( \theta_3 = 24.6^\circ, \varphi = 339.4^\circ \).

As analysis above, the property of polarization dependent for controlling terahertz wave scattering has been successfully verified by the coding PB phase metasurfaces with the regular coding sequences. To verify the polarization insensitive and broadband for suppressing the backward scattering characteristic of designed coding PB phase metasurfaces, numerical simulations were performed using CST Microwave Studio to calculate the bi-static radar cross section (RCS) of 1-bit, 2-bit, and 3-bit coding PB phase metasurfaces with random coding sequences generated by MATLAB under LCP, RCP and LP wave normal incidence at 1.0 THz. Fig. 9(a)–(c) exhibit the 1 bit, 2-bit and 3-bit random coding PB phase metasurfaces, respectively. Since the phase distribution on the random coding PB phase metasurfaces is randomly distributed, it redirects the incident terahertz wave energy to numerous directions and generates a lot of side lobes with the smaller energy which greatly suppresses backward scattering waves. The bi-static radar cross section (RCS) distribution of the three kinds of the coding PB phase metasurfaces and a same size bare metal plate have been simulated under the LCP, RCP and LP wave vertical incidence at 1.0 THz, as depicted in Fig. 10. Furthermore, the terahertz waves are reflected into numerous orientations and the maximum RCS reduction is approximately \(-20 \text{ dB}\). In addition, it is also found that the 3-bit random coding PB phase metasurface has the stronger ability to suppress the backward scattering than the 1-bit and 2-bit random coding PB phase metasurfaces.

The mechanism for the RCS reduction is achieved by redirecting reflective energy of terahertz wave in numerous directions through the coding PB metasurface. Under the normal incidence of
Fig. 9. Random coding PB phase metasurfaces. (a) 1-bit, (b) 2-bit, (c) 3-bit random coding PB phase metasurfaces.

Fig. 10. Bi-static RCS distribution for the coding PB phase metasurfaces and bare metal plate under normal incidence of the LCP (a), RCP (b) and LP (c) waves at 1.0 THz.
plane wave, the far-field pattern function of the coding PB metasurface is expressed as

\[ f(\theta, \varphi) = f_e(\theta, \varphi) \sum_{m=1}^{M} \sum_{n=1}^{N} \exp \left\{ -i \left[ \varphi (m, n) + KD_x \sin \theta \left( m - \frac{1}{2} \right) \cos \varphi + KD_y \left( n - \frac{1}{2} \right) \cos \varphi \sin \varphi \right] \right\} \]

where \( \theta \) is the elevation angle of an arbitrary direction, \( \varphi \) is the azimuth angle of an arbitrary direction, \( f_e(\theta, \varphi) \) is the pattern function of a lattice. The directivity \( \text{Dir}(\theta, \varphi) \) of the random coding PB metasurface can be given by

\[ \text{Dir}(\theta, \varphi) = \frac{4\pi |f(\theta, \varphi)|^2}{\int_0^{2\pi} |f(\theta, \varphi)|^2 \sin \theta d\theta d\varphi} \]

where the \( f_e(\theta, \varphi) \) is eliminated because of the phase difference of the “000” and “100”, “001” and “101”, “010” and “110”, or “011” and “111” digital elements. By treating each digital element as a dipole radiation source, the far-field radiation characteristics can be explained by the interference and superposition principle of electromagnetic wave for these digital elements. In our design, the reflection responses of these digital elements have basically identical amplitudes, but the reflection phase different is approximately 180° between “000” and “100”, “001” and “101”, “010” and “110”, or “011” and “111”. Therefore, the \( f_e(\theta, \varphi) \) of a lattice is eliminated due to the destructive interference between digital elements. Therefore, the RCS reduction can be achieve by the coding metasurfaces comprised by random coding sequences.

In order to verify the coding metasurfaces have the ability of reducing the RCS in a wide band. The RCS versus frequency ranging from 0.6 THz to 2 THz of both same size bare metal plate and coding metasurfaces under normal incidence LCP, RCP and LP waves are calculated as shown in Fig. 11. Compared with metallic plate, the RCS is reduced more than 10 dB from 0.8 THz to 1.6 THz. According to the figure, it is found that the maximum RCS reduction values of 1-bit, 2-bit
and 3-bit random coding metasurfaces are $-24.4$ dB, $-20.9$ dB and $-22.9$ dB, respectively. In detail, the RCS reduction values at 0.6 THz and 2 THz are smaller than those of other frequency because the reflection phase values of the basic unit cell between $x$- and $y$-polarized are not 180° at this time. Additionally, for the 1-bit random coding metasurface, the RCS values under LP wave normal incidence are slightly fluctuating compared with those of LCP and RCP waves normal incidence without influence on the bandwidth characteristics. For the 2-bit and 3-bit random coding metasurfaces, the RCS values under the RCP, LCP and LP waves normal incidence are not any change at the frequency range from 0.6 THz to 2 THz. This proves that the coding PB phase metasurfaces have polarization dependence property in reducing RCS.

In addition, we also simulated the near-field energy distribution of the 1-bit, 2-bit and 3-bit random coding PB phase metasurfaces in a vertical plane at 0.6 THz and 1.0 THz under normal illumination of LP waves, as depicted in Fig. 13. Obviously, Fig. 12(a)–(b), Fig. 12(c)–(d), and Fig. 12(e)–(f) show the near-field energy distribution of the 1-bit, 2-bit and 3-bit random coding PB phase metasurfaces at 0.6 THz and 1.0 THz, respectively. From the figures, one can see that only a far-field scattering beam generates at 0.6 THz for 1-bit, 2-bit and 3-bit coding metasurfaces, because the phase difference between $x$-polarized and $y$-polarized incidence is away from 180° and the effect of redirecting the normal incidence wave to numerous directions is insignificant, hence no RCS reduction occurs at this time. But at 1.0 THz, 180° phase difference produces between $x$-polarized and $y$-polarized incidence, and the RCP, LCP and LP normal incidence plane wave is redirected to all direction and RCS reduction is obtained, which is attribute to the disordered phase distribution of the random coding PB phase metasurfaces.

4. Conclusion

Based on the PB phase, we designed the regular and random coding metasurfaces to control the reflected terahertz waves. For pre-designed regular coding sequences, the terahertz waves are reflected into the desired orientations with polarization dependent property under normal incidence of the LCP, RCP and LP waves. Furthermore, 1-bit, 2 bit, and 3 bit random coding metasurfaces are designed by the random coding sequences, which can strong suppress the backward scattering of the bare metallic plate and redirect the normal incidence plane wave to numerous directions due to the disorder phase distribution of the coding PB phase metasurfaces. The RCS is reduced to $-10$ dB in a wide frequency band from 0.8 THz to 1.6 THz with the ability of polarization insensitive. The results demonstrated that the coding PB phase metasurfaces provide the ability of the wide-band RCS reduction and flexible way for the manipulation of the reflected terahertz wave.
References


