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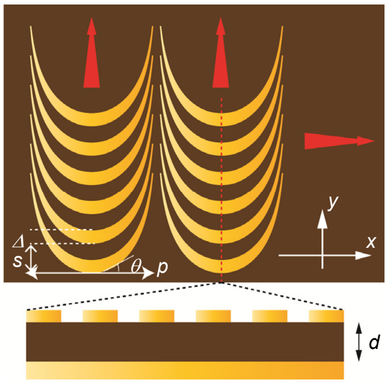
Anomalous scattering-induced circular dichroism in continuously shaped metasurface



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Abstract: The interconnection of polarization and phase in electromagnetic scattering process has attracted both fundamental and practical interest. Here we propose the principle and experimental demonstration of a scattering-control mechanism based on the simultaneous control of polarization and phase via a continuously shaped planar metasurface. Under circularly polarized illumination, the scattering is redirected to off-specular direction, leading to significant reduction of the scattering cross section. Theoretical investigation shows that the underlying physical mechanism is the spin-dependent phase modulation in the anisotropic scattering process. Our approach would provide valuable guidance for the full control of electromagnetic wave for diverse applications.

Keywords: scattering engineering; circular dichroism; continuously shaped metasurface

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1 Introduction

Although the linearly polarized beam splitter based on the birefringent effect has been well known since its discovery in 1800s, its circular counterparts have only recently been made possible. In essence, the difference in light-matter interaction for circularly polarized fields, termed as circular dichroism (CD), is stemming from the chiral molecule structure. The CD provides an important but inefficient way to probe the micro-structure of biological molecules. To enhance the CD signal, a vast range of technologies including superchiral structures, magnetic field and orbital angular momentum induced CD have been proposed[1]. Particularly, chiral metamaterials, composed of artificial meta-atoms with controllable chirality, have received great attention[2–4].

Recent experiments have shown that planar metasurface can also lead to CD at oblique incidence, albeit it is typically thought that chiral structure must contain non-mirror symmetry[5-8]. Except from the chiral geometry in a single unit cell of metasurface[9-11], space-variant anisotropic meta-atoms are also able to support polarization-dependent phenomenon. The spin-orbit interaction in metasurface is responsible for the different behaviors of circular polarizations[12-16]. In typical spin-orbital metasurface, the unit cell of metasurface is isolated and responsible for a discrete phase and amplitude level[17–20]. Gradient metasurface can be then obtained by changing the geometrical parameters of individual unit cells[21–23]. Nevertheless, the discrete phase and amplitude modulations lead to some degradation of the overall performances. What's more, the metal-dielectric compound system is not electrically conductive, thus it is difficult to obtain simultaneous electric and optical functionality. Quite recently, semi-continuous super-meta-atoms including catenary[13, 24-25] and trapezoid shaped structure[26] as well as true-continuous super-meta-atoms including annular slits[16, 27] and centenary metallic strips[15] have been adopted in metasurfaces to overcome the shortages mentioned above.

In this letter, we provide a novel continuously shaped super-meta-atom with compound optical characteristic. Under circularly polarized illumination, the reflected wave is redirected with a polarization-dependent angle with respect to the specular reflection direction. Finally, we show that our structure is able to reduce the monostatic radar cross section (RCS) dramatically.

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2 Theory

The geometry of the metasurface is illustrated in Fig. 1, where only six rows and two columns of catenary-shaped metallic patches are given. The catenary profile is determined by a function widely used in architectures since its first discovery in 1826 by Davies Gilbert[28]:

$$y = \frac{p}{\pi}\ln[\,|\sec(\frac{\pi x}{p})|\,], \tag{1}$$

where x and y are the positions in Cartesian coordinate and p is the horizontal length of the catenary structure. The anisotropic and inhomogeneous metallic structure can be considered as a serial of anisotropic subwavelength meta-atoms with space-variant orientation angle, thus is subjected to the famous spin-obit interaction (SOI)[29].

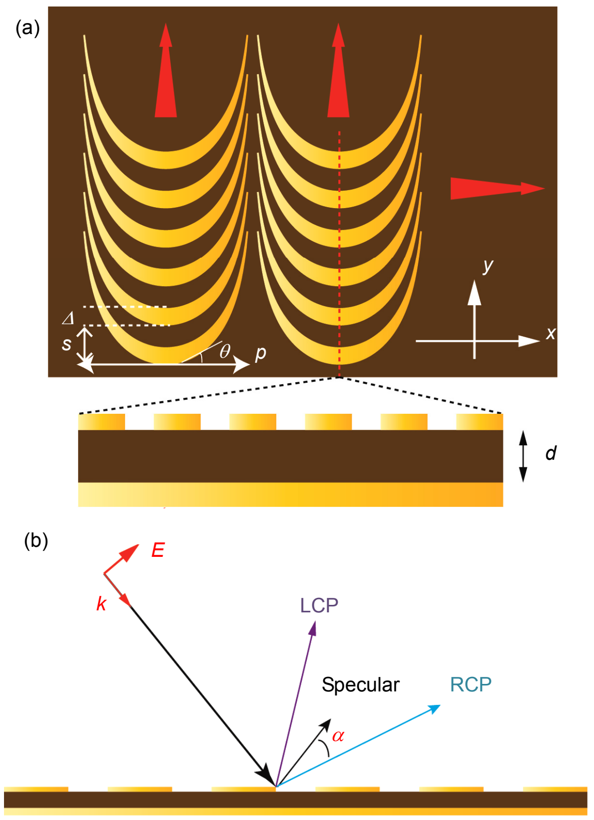

Fig. 1 Principle of the operation. (a) Geometry of the catenary array. (b) Schematic of the polarization-dependent reflection.

In our design, a metallic ground plane and a dielectric substrate are added below the metasurface. Consequently, the entire incident electromagnetic (EM) wave would be reflected back. When the thickness of the dielectric spacer is adjusted properly, the metasurface, dielectric spacer, and the metallic ground plane would form a space-variant waveplate. For half-wave plate, circular polarization would be reversed after reflection[30-32], with a space variant geometric phase, which is just twice the inclination angle of anisotropic subwavelength meta-atoms. According to the principle of geometric phase, we can obtain the phase modulation along the inhomogeneous catenary profile defined in the equation (1):

$$\Phi(x,y) = 2\sigma\theta = 2\sigma\arctan\left(\frac{\delta y}{\delta x}\right)\bigg|_x = \frac{2\sigma\pi x}{p}, \tag{2}$$

where $\sigma = \pm 1$ denotes the handedness (i.e., left or right, respectively) of the incident circular polarizations. According to the equation (2), dispersion-free linear phase change covering 2π can be generated within single unit cell (x changes from $-p/2$ to $p/2$), a mission that is extremely difficult if not impossible for state-of-art technology[13]. It should be noted that the geometric phase in catenary is free of discrete phase abruption as in the case of nano-antenna arrays[14]. The elimination of discreteness implies that it is possible to move an important step towards the metasurface-assisted law of reflection and refraction[33-34] and promise high purity of orbital angular momentum[16].

When illuminated with linearly polarized wave, two circular waves which undergo different deflection must be considered. The anomalous reflection angle θ_r can be calculated by:

$$\theta_r = \arcsin\left(\frac{\lambda}{2\pi}\frac{d\Phi}{dx}\right) = \arcsin\left(\frac{\sigma\lambda}{p}\right). \tag{3}$$

Through transfer matrix method, the whole reflection electric field can be written as:

$$\begin{bmatrix}E_x\\E_y\end{bmatrix} = \frac{1}{2}\exp\left(\mathrm{i}\frac{2\pi x}{p}\right)\begin{bmatrix}1\\-\mathrm{j}\end{bmatrix} + \frac{1}{2}\exp\left(-\mathrm{i}\frac{2\pi x}{p}\right)\begin{bmatrix}1\\\mathrm{j}\end{bmatrix} = \begin{bmatrix}\cos(2\pi x)\\\sin(2\pi x)\end{bmatrix}. \tag{4}$$

3 Simulations and experiments

The proposed metasurface, owing to the continuous phase profile as well as powerful scattering engineering ability, is taken as a promising approach for electromagnetic cloak or electromagnetic illusion[12, 35-36], a strategy used to make an object of arbitrary shape and material properties appears exactly like another object of some other shape and material makeup. Subsequently, full model simulations are carried out to verify the reduction of monostatic radar scattering section (RCS). In the simulation, the meta-mirror has a thickness of 3 mm and lateral dimension of 314 mm × 314 mm. The period of the catenary metallic strips along y direction is s = 10 mm, less than the incident wavelength λ to prevent the diffraction in yoz plane. The period of the catenary metallic strips along x direction is p = 62.8 mm, larger than the incident wavelength λ to generate high efficiency beam deflection. The width of catenary metallic strips is Δ = 5 mm to obtain high polarization conversion efficiency around 9 GHz. Since the simulation is carried out the microwave band, the loss of metal structure is tiny, and thus PEC mode is selected in the simulations.

Fig. 2(a) shows the monostatic RCS of metallic reflection plane and the proposed metasurface in X band (8~12 GHz). One can find that the RCS of proposed metasurface is lower than that of metallic reflection plane in the whole X band. Especially, the maximum of the RCS reduction exceeds 20 dB around the 8 GHz and 9.4 GHz for transverse electric (TE) and transverse magnetic (TM) polarization, respectively. In order to get physical insight of RCS reduction, the RCS of proposed metasurface under the illumination of RCP and LCP at 9.4 GHz is investigated and presented in Fig. 2(b). We can find that the centenary metasurface proposed here with the gradient phase stemming from the SOI forces the reflected beam of opposite handedness to propagate in well-defined directions. The simulated deflection angle at 9.4 GHz is ±30.5° with respect to the normal direction, agreeing with the theoretical value of 30.7° from Eq. (3). It should be noted that, although the geometric phase origin from SOI is frequency independent, the wavelength and polarization conversion efficiencies vary at different frequencies. Therefore, the scattering angular spectra presented in Fig. 2(c) change with the frequency and the abnormal deflection angle decreases with the incident frequency, which is consistent with the results presented in previous literature[15].

The reflected electromagnetic fields for two frequencies (8 GHz and 9.4 GHz) are depicted in Fig. 3. As predicted by Eq. (4), the whole reflection electric fields are formed by the interference between the field $\sin(2\pi x)$ and $\cos(2\pi x)$. The constant phase fronts unambiguously demonstrate the presence of anomalous refractions are 36.5° and 30.5° at 8 GHz and 9.4 GHz, which is consistent with the theoretically calculated values of 36.8° and 30.7°. In fact, at the two frequencies mentioned above, the proposed metasurface can be taken as a simple circular beam splitting structure supporting background-free circular components in two distinct diffraction directions.

In order to prove the numerical results, a sample was fabricated with print circuit board (PCB) technique as shown in Fig. 4(a). Reflection measurements were taken in a microwave anechoic chamber with a network analyzer, as shown in Fig. 4(b). Two standard linearly polarized horn antennas (the electric field is parallel to x axis) as transmitter and receiver, respectively, were connected

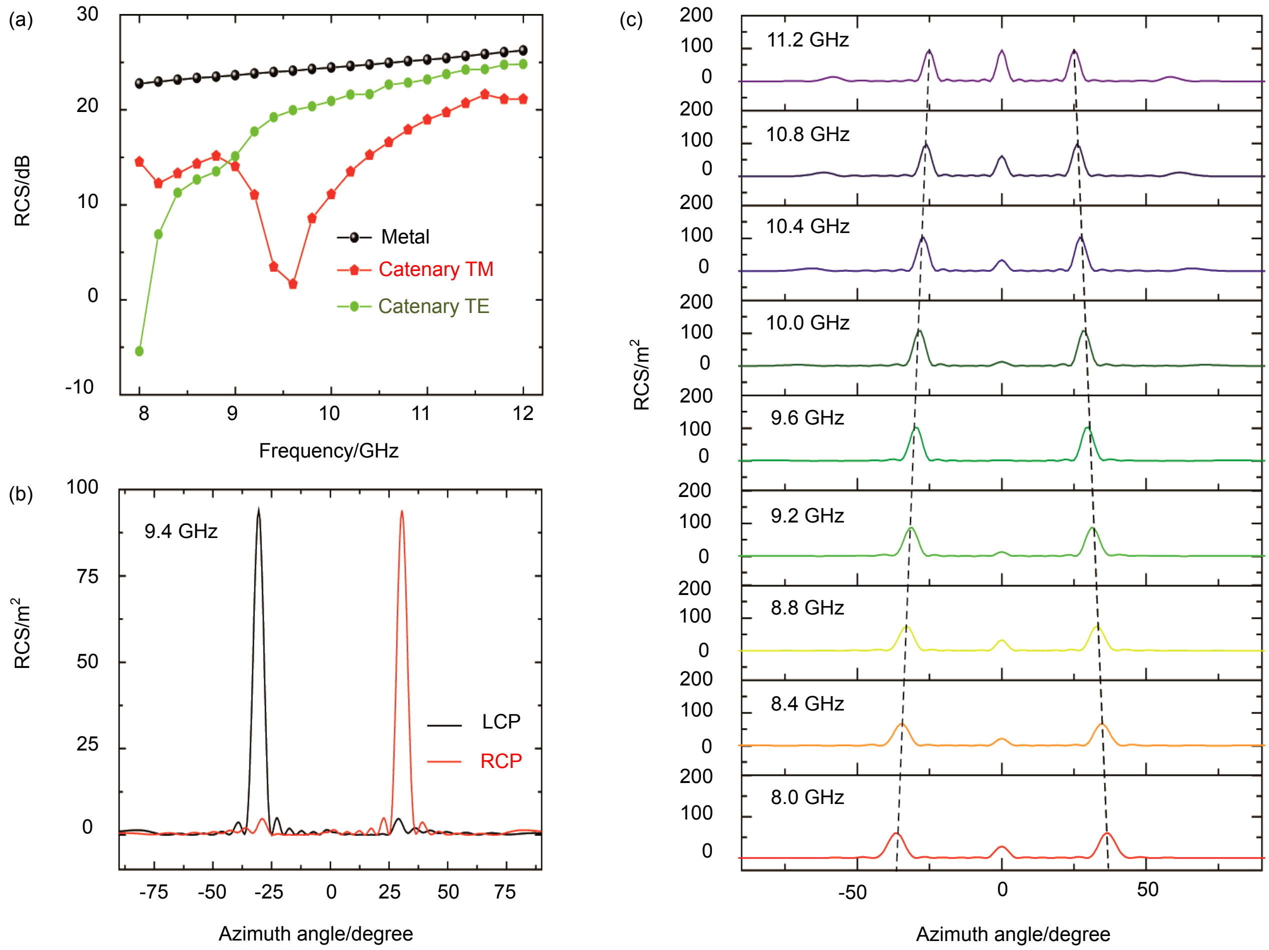

Fig. 2 Simulations of the structure. (a) RCS of the array compared with PEC for TE and TM polarizations. (b) RCS in the incidence plane as a function of azimuth angle for LCP and RCP incidence at 9.4 GHz. (c) 2D RCS for frequencies ranging from 8 GHz to 11.2 GHz. The two dashed lines indicate the dispersion of the diffraction angle.

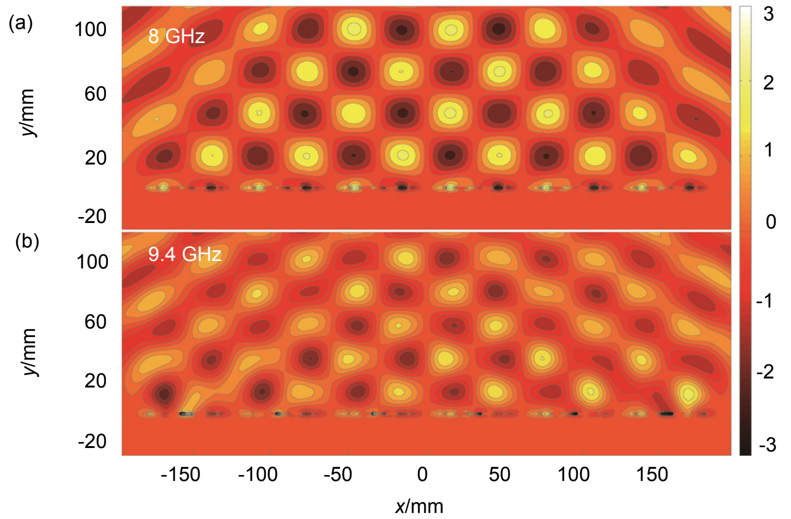

Fig. 3 Calculated electric field distributions. (a) f = 8 GHz. (b) f = 9.4 GHz.

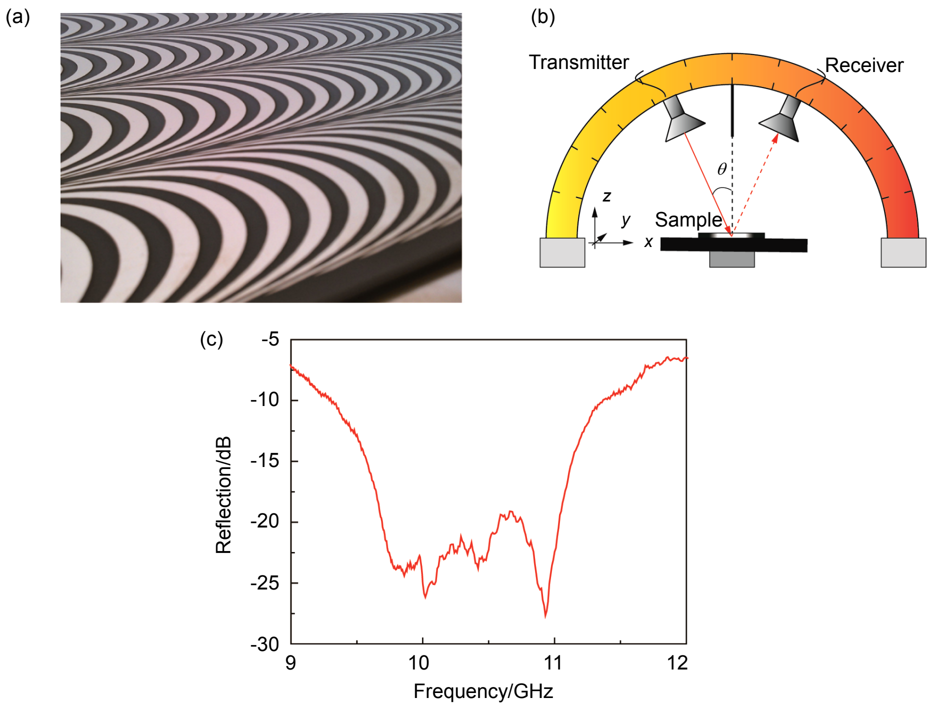

Fig. 4 Fabrication and characterization of the sample. (a) Photograph of the sample. (b) Schematic of the measurement setup. (c) Measured reflection for the sample.

to the two ports of a vector network analyzer R&S ZVA40. The incident angle was set as 5°, which is a good approximation of the normal incidence. The results shown in Fig. 4(c) display reflection reduction of 20 dB from 9.7 GHz to 11 GHz, which is in reasonable agreement with the simulated results in Fig. 2(a), considering the imperfection in the fabricating and measuring process.

4 Conclusions

In summary, the circular dichroism in continuously shaped metasurface is investigated, which is a result of the spin-orbit interaction in spatially inhomogeneous catenary metallic stripes. The abnormal scattering behavior of circularly polarized electromagnetic waves decreases the RCS of the underneath object, which may find applications in stealth technology. Although the proposed metasurface is only demonstrated in microwave frequency, it is no doubt that this tactics can be extended to infrared and visible bands.

Acknowledgements

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