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基于旋转超表面的相干自旋霍尔效应的可调光束

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Dynamical optical beam produced in rotational metasurface based on coherent spin hall effect

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Abstract: Based on the spin Hall effect of photons, a metasurface can be used to generate and control light beams. In this paper, by means of one-dimensional chains of nanohole, a metasurface with rotational symmetry is designed. The Bessel beam can be produced by the spin Hall effect of Left-handed Circularly Polarized (LCP) and Right-handed Circularly Polarized (RCP) light simultaneously. Through the excitation of linearly polarized light, we can dynamically control the intensity and polarization of Bessel beam by controlling the coherent interference between two circularly polarized light excitation beams. At the same time, this method has the advantage of broadband modulation range.
Key words: dynamically controllable bessel beam; metasurface; broadband modulation range

基于旋转超表面的相干自旋霍尔效应的可调光束

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摘要:基于光子的自旋霍尔效应,超表面可用于光束的产生和控制。本文基于旋转变换利用一维纳米孔链设计了二维纳米孔旋转对称超表面。利用此样品,可以由左旋圆偏振(LCP)和右旋圆偏振(RCP)光的自旋霍尔效应同时产生贝塞尔光束。利用线偏振光激发,通过控制两个圆偏振光激发光束之间的相干干涉可动态调控贝塞尔光束的强度和偏振。同时,此方法还具有宽带调制的优点。
关　键　词:动态可控贝塞尔光束;超表面;宽带调制范围
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1 Introduction

Light beams have important applications in optical communications, optical manipulations, optical imaging, laser processing and other fields[1-2]. Therefore, the generation, detection and dynamic control of light beams have attracted intensive research interest in the field of optics. In recent years, metasurfaces have been proposed to control the propagation of electromagnetic waves[3-8]. Metasurfaces are also used to generate optical beams through the interaction between structural units and light waves, and thus the generation and control of various beams have been achieved[9-19]. For example, people use a metasurface to generate Bessel beams.

In addition to the two-dimensional metasurfaces, another simpler one-dimensional chain of metamaterials has also been proposed to control light. For example, one can use a one-dimensional nanohole chain to simulate Cherenkov radiation of moving particles[20] or the bremsstrahlung of accelerating particles[21] through the photon spin Hall effect, which can be used to generate and modulate SPP beams. Furthermore, SPP surface wave holograms can be dynamically controlled through the interference between two beams of circularly polarized light, LCP and RCP, based on the coherent spin Hall effect[22]. In most work on the spin Hall effect, when considering the interaction between incident light and a metallic nanohole on the metasurface, the cross-polarization term is controlled by the PB phase (Pancharatnam-Berry phase)[23-24] is most often considered, while the co-polarization term is often ignored. This is because this co-polarization term traditionally plays the role of background noise and should be eliminated. Here, we have a contrary approach and utilize this term to interfere with the cross-polarization term in order to build up a new avenue to modulate the optical beam.

In this paper, we use one-dimensional chains of nanoholes to construct a two-dimensional nanohole metasurface with rotational symmetry through rotation transformation. If we illuminate this metasurface with circularly polarized light, we can obtain a Bessel beam. From the results, we demonstrate that the co-polarization term has a non-negligible contribution in the formation of the polarized modulated Bessel optical beams in both theoretical and experimental applications for the first time. By controlling the polarization of the incidence, we can dynamically control the polarization and intensity of the optical beam. Moreover, our sample can work in a large range in wavelength with the wavelength-dependent transmission distance. Therefore, the dynamically controllable Bessel beam realized by our designed metasurface can be good candidates in many applications such as modulators in optical communications.

2 Theoretic design

In the previous work, we used one-dimensional nanohole metamaterials to generate SPP (Surface Plasmon Polaritons) beams on metal surfaces by simulating Cherenkov radiation in moving particles based on spin Hall effect. Then, we asked whether this one-dimensional metamaterial can be used to generate a light beam in free space? In this paper, based on one-dimensional metamaterials, we designed a two-dimensional metasurface structure by rotation transformation. More specifically, we designed different one-dimensional metamaterial chains for LCP and RCP light. Then, we transformed these chains to form a two-dimensional metasurface with rotational symmetry. Finally, we combined the two kinds of metasurfaces to form a structure that can generate light beams from both LCP and RCP incident waves at the same time. In the following part, we gave the specific theoretical design process.

In paraxial approximation, we established a cylindrical coordinate to describe the scattering electric field near the z-axis of a metallic nanohole at $(\rho_0, \theta_0, 0)$ when a circularly polarized light of frequency ω_0 was normally illuminated[25]:

$$\boldsymbol{E}(\rho,\theta,z) \approx \frac{c\alpha_{\mathrm{e}} k^2 \mathrm{e}^{(ikr)}}{4\sqrt{2}\pi r} \frac{\frac{z}{r}+1}{4} e^{-\frac{\rho^2}{\omega_0^2}} (\boldsymbol{E}_u^{-\sigma} \mathrm{e}^{(+\sigma i 2\varphi(\rho_0,\theta_0))}). \quad (1)$$

This equation was obtained according to the paraxial condition: $kr >> 1$ and was considered a cross-polarization term only, where c is the speed of light in a vacuum, k is the wave vector, α_{e} is the electric dipole moment of the antenna, r is the distance from the metallic nanoholes to any point in space, and ζ is the refraction angle. $\boldsymbol{E}_u^{\pm\sigma} = (\cos\zeta \mathbf{e}_x \pm \sigma i \mathbf{e}_y - \sin\zeta \mathbf{e}_z)$ and $\sigma = \pm 1$(RCP: +1/LCP: -1) describe the properties of the incidence.

To theoretically show the results of our designed metasurface, we calculated the electric field along the z-axis of our designed metasurface. The metallic nanoholes on the radius at a given angle were started at a specified orientation and then rotated uniformly. Then, this action was repeated at different angles with rotational symmetry in each of the positions of the nanoholes. Thus, by the integral of Eq.(1) in ρ_0 and θ_0, the intensity of the x-component of the electric field along the z-axis can be obtained:

$$\begin{cases} \boldsymbol{E}_{\mathrm{cro}} = \boldsymbol{E}_x + \boldsymbol{E}_y + \boldsymbol{E}_z \;\; 2\sigma k_{\varphi}\rho \in \mathrm{Reals} \\ E_x = \dfrac{c\alpha_{\mathrm{e}} k^2}{4\sqrt{2}\pi} F(z) e^{-\frac{\rho^2}{\omega_0^2}} (-\pi \mathrm{J}_0(\mathrm{Abs}(2k_{\varphi'}\rho))) \\ E_y = -\sigma i E_{XT} = -\sigma i \dfrac{c\alpha_{\mathrm{e}} k^2}{4\sqrt{2}\pi} F(z) e^{-\frac{\rho^2}{\omega_0^2}} (-\pi \mathrm{J}_0(\mathrm{Abs}(2k_{\varphi'}\rho))) \\ E_z = \dfrac{c\alpha_e k^2}{4\sqrt{2}\pi} G(z) e^{-\frac{\rho^2}{\omega_0^2}} (-\pi \mathrm{J}_0(\mathrm{Abs}(2k_{\varphi'}\rho))) - \pi A \dfrac{1}{2\beta} \dfrac{e^{ikz}}{z^2} e^{ik\frac{\rho^2}{2z}} \\ F(z) = \dfrac{1}{2} \dfrac{e^{ikz}}{z} e^{-\frac{\gamma^2}{4\beta}} \sqrt{\dfrac{\pi}{\beta}} \cdot \mathrm{Erfc}\left((1-i)k_{\varphi'}\sqrt{\dfrac{z}{k}}\right) \\ G(z) = \left(-\dfrac{i}{8}\sqrt{\dfrac{\pi}{\beta^3}}\right) \dfrac{e^{ikz}}{z^2} \gamma e^{-\frac{\gamma^2}{4\beta}} \cdot \mathrm{Erfc}\left((1-i)k_{\varphi'}\sqrt{\dfrac{z}{k}}\right) \end{cases} \quad (2)$$

where $\beta = (1/\omega_0^2) - (ik/2z)$, $\gamma = -\sigma 2k_{\varphi}$, $\varphi(x_0)$ is the rotation angle of the nanoholes at x_0, $k_{\varphi'}$ denotes the absolute value of the gradient of the nanoholes' orientations along the radius, and $k_{\varphi} = \sigma k_{\varphi'}$. For $F(z)$ and $G(z)$ in Eq. (2), E_z can be ignored compared to E_x because of paraxial approximation. Similarly, the field generated by the co-polarization term can also be calculated without the PB phase:

$$\begin{cases} \boldsymbol{E}_{\mathrm{co}} = \boldsymbol{E}_x' + \boldsymbol{E}_y' + \boldsymbol{E}_z' \\ E_x' = \dfrac{c\alpha_{\mathrm{e}} k^2}{4\sqrt{2}\pi} B(z) \mathrm{J}_0(\dfrac{k\rho^2}{4z}) \\ E_y' = \sigma i \dfrac{c\alpha_{\mathrm{e}} k^2}{4\sqrt{2}\pi} B(z) \mathrm{J}_0\left(\dfrac{k\rho^2}{4z}\right) \\ E_z' = i\pi \dfrac{c\alpha_{\mathrm{e}} k^2}{4\sqrt{2}\pi} \dfrac{1}{k} \dfrac{e^{ikz}}{z} \mathrm{e}^{\frac{ik\rho^2}{2z}} \\ B(z) = \pi \dfrac{\mathrm{e}^{ikz}}{z} \sqrt{\dfrac{\pi z}{2ik}} \mathrm{e}^{(ik\frac{3\rho^2}{4z})} \end{cases} \quad (3)$$

For the calculation results above, the cross-polarization term and co-polarization term from the interaction between circularly polarized light and dipoles were both considered in order to construct the optical beam. The utilization of the co-polarization term provides another degree of freedom in the generation of a structured beam.

3　Experimental results

Fig. 1(a) and (b) show the schematic of designed metasurface by rotated chains of nanohole arrays, and the designed nanohole with configuration angle. A fabricated sample is shown in Fig. 1(c). A 30 nm layer of silver, a 50 nm layer of silicon dioxide and another silver layer of 70 nm were continuously deposited onto the silicon dioxide substrate to form a sandwich multilayer structure of Ag-SiO_2-Ag. The nanohole pattern was fabricated on the top silver layer using a focused ion beam (FEI Strata FIB 201, 30 keV, 7 pA). Fig. 1(e) presents the schema of the experimental setup used in our optical measurement. We used a femtosecond laser to generate near-infrared 1 040 nm linearly-polarized light to illuminate the metasurface sample, and then the output laser beam was detected using a s-CMOS camera.

We scanned the light field for a distance of z with a s-CMOS camera, and measured the optical field along the z-axis. For the two circularly polarized lights, we designed two sets of chains on the same sample, as shown in Fig. 1(d). There are eight nanochains designed for left-handed circularly polarization intersecting with another eight nanochains for right-handed circularly polarization. Each chain contains 20 nanoholes. The first nanohole of each chain is 3.6 μm away from the center of the pattern. The distance between each of the two nanoholes is 600 nm. For the chain designed for the left-handed spin, the (n+1)-th nanohole rotates π/5 counterclockwise relative to the n-th nanohole. For the chain designed for the right-handed spin, the (n+1)-th nanohole rotates π/5 clockwise relative to the n-th nanohole. Fig. 1(c) is the lateral view of the sample obtained by an SEM (Scanning Electron Microscope), and the insert of Fig. 1(c) shows the periodically distributed nanoholes.

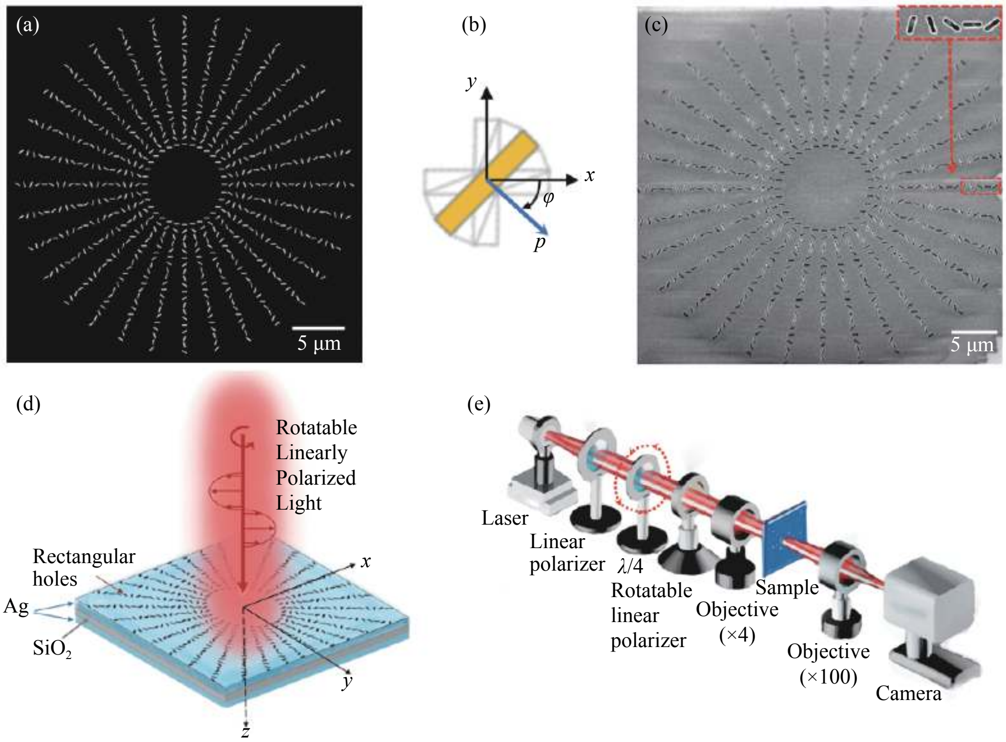

Fig. 1 (a) Schematic of designed metasurface from the rotated chains of the nanohole arrays; (b) designed nanohole with configuration angle φ; (c) sample picture of the rotated metasurface fabricated by a focused ion beam; (d) illuminating rotated metasurface with a circularly polarized laser beam; (e) Optical experiment setup

The captured two-dimensional light field pattern of the optical beam through a s-CMOS camera is the result of the circularly polarized light interacting with the sample. The calculated light intensity distribution in the x-y plane (at z=15 μm) is presented in Fig. 2(a, c) while the matching experimental results are shown in Fig. 2(b, c).

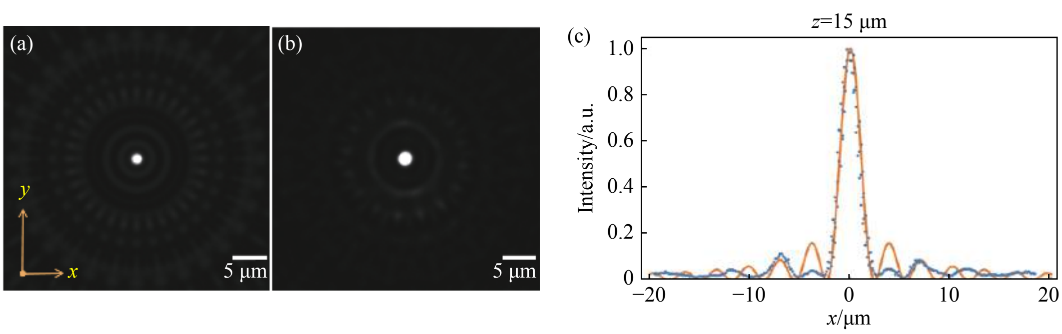

Fig. 2 Beam spot profile at z=15 μm produced by the rotated metasurface illuminated by circularly polarized incident light. (a) From theoretical calculation; (b) from experimental measurement; (c) intensity distribution curves of beam spot along a central line (blue dots: from measurement; orange curve: from calculation)

In the experiment, we designed two kinds of nanohole chains. One is to generate Bessel beams for LCP excitation, and the other is to generate the same Bessel beams for RCP excitation. Then we rotated the two chains alternately to obtain the composite metasurface with rotational symmetry. The structural design and experimental samples are shown in Fig. 1(a, b) and Fig. 1(c), respectively. In this composite structure, both LCP and RCP can excite the sample to produce the same Bessel beam. Fig. 2 shows the output beam field profile excited by LCP. Fig. 2(a) gives the theoretically calculated result, and Fig. 2(b) gives the experimentally measured result. Both theoretical and experimental results show that RCP and LCP can produce the same beam separately for our composite structure, and the theoretical and experimental results agree. We know that the linearly polarized light can be regarded as the superposition state of LCP and RCP light. Therefore, if we use the linearly polarized light to excite the metasurface sample, the generated beam can also be regarded as the coherent superposition state of LCP and RCP light. The phase difference between LCP and RCP depends on the polarization direction of linearly polarized light. As long as we continuously change the polarization direction, we can continuously change the interference between the beams generated by LCP and RCP, which can continuously change the beam intensity. Fig. 4 shows that the curve of the beam center intensity increased with the polarization angle ψ. The corresponding results for the three polarization angles are shown in Fig. 3 ($\psi = 0, \pi/2, \pi$). We can see from the photo of the intensity profile of the beam spot produced by the sample excited with the varied linearly polarized angle ψ that the intensity of the light spot decreases continuously with an increase of ψ.

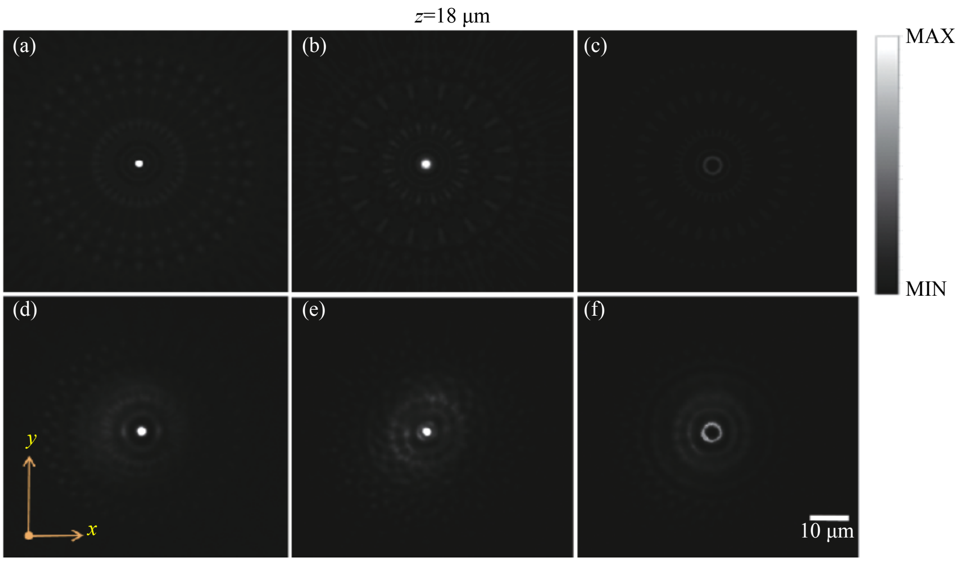

Fig. 3 Beam spot profile at z=18 μm produce by the rotated metasurface illuminated by a linearly polarized incident light with polarized angle $\psi = 0, \pi/2, \pi$. (a-c) From theoretical calculation; (d-f) from experimental measurement

Using our metasurfaces, we can dynamically control the intensity and polarization of a Bessel beam. In order to detect the polarization characteristics of the beam, we put a polarizer in front of the sample and an analyzer behind the sample as shown in Fig. 1(e). In the experiment, we rotated the polarizer to change the polarization direction of the incident light on the sample. At the same time, we detected the polarization state of the output light through the analyzer behind the sample. The intensity of the beam spot under different incident polarizations is given in Fig. 5, which includes both the theoretical calculation (Fig. 5(a, b)) and experimental measurement (Fig. 5(c, d)). The experimental results show that when the polarizer is parallel to the analyzer, the intensity of the light spot is at its strongest (in

Fig. 5(a, c)), and when the polarizer is perpendicular to the analyzer, the intensity of the light spot is at its weakest (in Fig. 5(b, d)). For other polarization angles, the intensity of the light spot decreases continuously with an increase in the polarization angle. By comparison, our theoretical calculation is in good agreement with the experimental results. This dynamic control of light beams is quite simple and efficient through changing incident polarization.

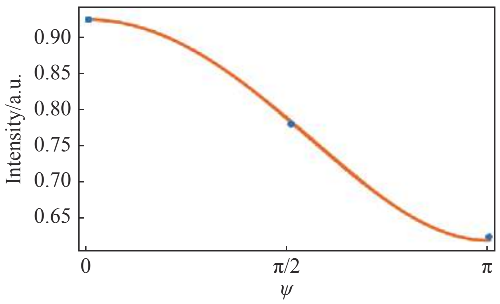

Fig. 4 Intensity of beam spot produced by rotated metasurface with varied polarized angle ψ (blue dots: from measurement; orange curve: from calculation)

In addition to the intensity and wavelength regulation discussed above, another advantage of the metasurface we designed is that it is insensitive to different wavelengths and has the characteristics of broadband regulation. In the theoretical calculation, we selected three laser illuminating samples with different wavelengths of 690, 865, and 1 040 nm. The calculated x-z section of the output beam is given in Fig. 6. The results show that the metasurface can produce good Bessel beams at these three wavelengths. Although their transmission is reduced with the increase of wavelength, the beam is still able to maintain good non-diffractive transmission.

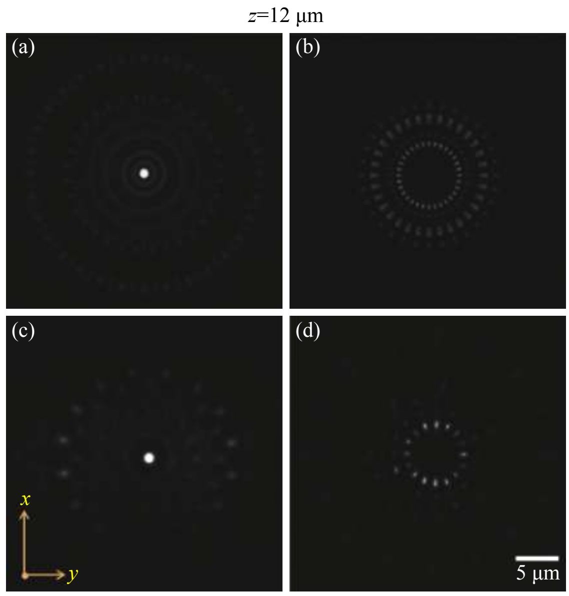

Fig. 5 Detecting the polarization state of the output beam spot from rotated metasurface with linearly polarized light. A polarizer is put in front of the sample and an analyzer is put behind the sample. (a, c) the analyzer is parallel to polarizer; (b, d) the analyzer is perpendicular to the polarizer

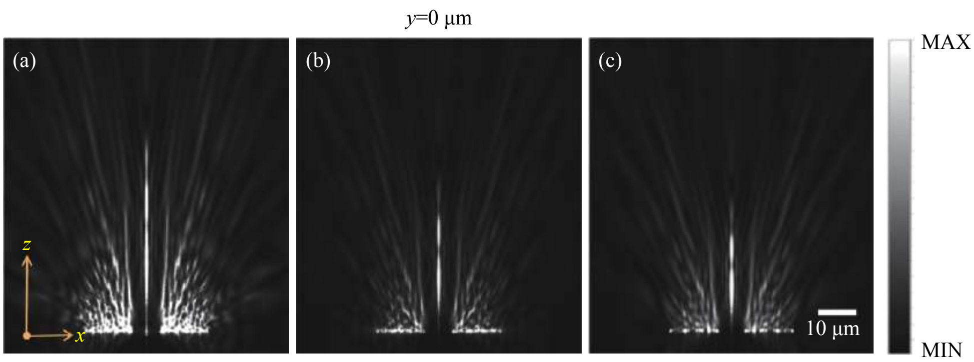

Fig. 6 The calculated laser beam produced by the rotated metasurface illuminated by a circularly polarized light with three different incident wavelengths. (a) λ=690 nm; (b) λ=865 nm; (c) λ=1 040 nm

4 Conclusion

In conclusion, one-dimensional nanohole metamaterials were used to construct a rotationally symmetric metasurface by rotation transformation. Using the interference between two beams produced by LCP and RCP, we have realized a Bessel beam whose intensity and polarization can be dynamically controlled. The control function can be achieved in the wide-frequency band. The rotating metasurfaces reported in this paper provides a new kind of metasurfaces with a dynamic control function, which has potential future applications in photonic communication, dynamic imaging and other optical applications.

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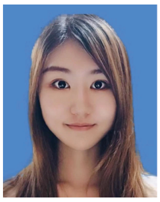

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