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Invited Paper

Flat optics and ultrathin optical devices with unusual functionalities

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ABSTRACT

To meet the growing requirement of system integration, it is of great importance and interest to develop ultrathin optical devices with unusual functionalities. As one of the most rapidly expanding frontiers of nanophotonics, optical metasurfaces, or planar metamaterials with subwavelength thickness, have the potential to revolutionize classical optics by displacing refractive optics in many large-scale applications and creating completely new functionalities. Benefiting from the unprecedented capability of metasurfaces in the arbitrary control of light's amplitude, phase and polarization at subwavelength resolution, optical metasurfaces have provided us new opportunities to fully control the wavefront of light with planar elements and thus realize flat optics based optical devices. In this paper, I am going to highlight our work in dual-polarity metalens, multifunctional metalens, light sword lens, image-switchable holograms, arbitrary polarization manipulation for security, multichannel device for manipulation of twisted light beams and so on. The metasurface have provided unprecedented freedom in engineering the properties of optical waves with the high-efficiency light utilization and a minimal footprint for security and defence. The unique properties of these novel metadevices can bring many of the completely new instruments to our daily lives.

Keywords: Metasurface, metamaterial, nanostructure, ultrathin lens, hologram, orbital angular momentum, polarization manipulation.

1. INTRODUCTION

Metamaterials can allow engineers to design materials with electromagnetic properties unavailable in nature. Natural materials are made of atoms, while the metamaterials are made of the artificial building blocks that can be tailored at will. The unusual properties of metamaterials have attracted considerable interest from all over the world, leading to many breakthrough works, including invisibility cloaking, superimaging and negative refraction. Although metamaterials have brought new concepts and new ideas, the application of metamaterials in the optical range has been hindered by the fabrication challenge of three-dimensional (3D) nanostructures. To overcome the fabrication difficulties and high loss of metamaterials working in the optical range, two-dimensional metamaterials, or metasurfaces [1, 2] have been developed. Metasurfaces consist of a single layer of optical antennas or the stack of several layers to locally modify the phase, amplitude and polarization of the scattered light. Optical antennas are typically made of metals or high refractive index dielectric materials, which can be fabricated through standard nanofabrication process, such as electron beam lithography, lift-off process, focused ion beam milling or reactive ion etching, thus the complexity of the fabrication is greatly reduced in comparison with that for their 3D counterparts. Besides, metasurfaces can change the properties of the scattered light by using antennas with a dimension smaller than the operating wavelength, which exhibits high resolution and can avoid the higher diffraction orders of the traditional diffractive optical devices. In addition, the thickness of the metasurface is much smaller than the incident wavelength, which makes them more practical for device miniaturization and system integration.

The first phase-gradient metasurface was demonstrated by Capasso's group[1]. Upon the illumination of linearly polarized light, the V-shaped antennas with various arm lengths and opening angles can provide phase gradient to the cross-polarized light, which verifies the generalized laws of reflection and refraction. A two-dimensional array of V-shaped antennas is used to produce a linear phase gradient distribution. Anomalous reflection and refraction phenomena were observed by patterning periodically distributed nanoantennas, where each unit cell consists of eight different V-shaped antennas that can cover the whole $[0, 2\pi]$ phase range. Metasurfaces based on the Pancharatnam-Berry (PB) phase are associated with the change of polarization state of light. Huang et al. investigated dispersionless phase

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discontinuity by using the dipole nanorods[3]. In this approach, each dipole nanorod can be treated as an anisotropic scatterer which converts part of the incident circularly polarized (CP) light to its opposite helicity with an extra geometric phase whose absolute value equals to two times of the orientation angle of the dipole. Thus, a phase profile can be imparted to the scattered light from an array of dipole nanorods with designed orientations. The abrupt phase change is generated when a right circularly polarized (RCP) light beam is converted to its opposite helicity. An optical vortex beam with topological charge of one was demonstrated experimentally. Although this kind of optical metasurface device can work in the broadband, the efficiency is very low even at the resonance wavelength. To tackle the challenge of low efficiency while maintaining the property of broadband, the reflective metasurfaces[4] were proposed. This type of metasurface consists of three layers: the nanorods on the top, the metallic film at the bottom and the dielectric in the middle. Each nanorod along with the other two layers functions as a reflective-type half-wave plate, which can dramatically increase the efficiency and broadband. Apart from V-shaped structures and rod structures, other structures have also been developed in the last several years. Among these structures, metasurfaces consisting of dielectric nanopillars[5] are very attractive since they are highly efficient and compatible with most optical systems (transmission type). Each nanopillar function as a half waveplate, which can realize the polarization rotation of the linearly polarized light and can generate PB phase for the incident light with circular polarizations.

Benefiting from the unprecedented capability in the light manipulation, a plethora of metasurface devices with unusual functionalities have been developed. In this paper, I am going to highlight our work in dual-polarity metalens, multifunctional metalens, light sword lens, image-switchable holograms, arbitrary polarization manipulation for security, multichannel device for manipulation of twisted light beams and so on.

2. ULTRATHIN OPTICAL DEVICES WITH UNUSUAL FUNCTIONALITIES

2.1 Ultrathin metalenses

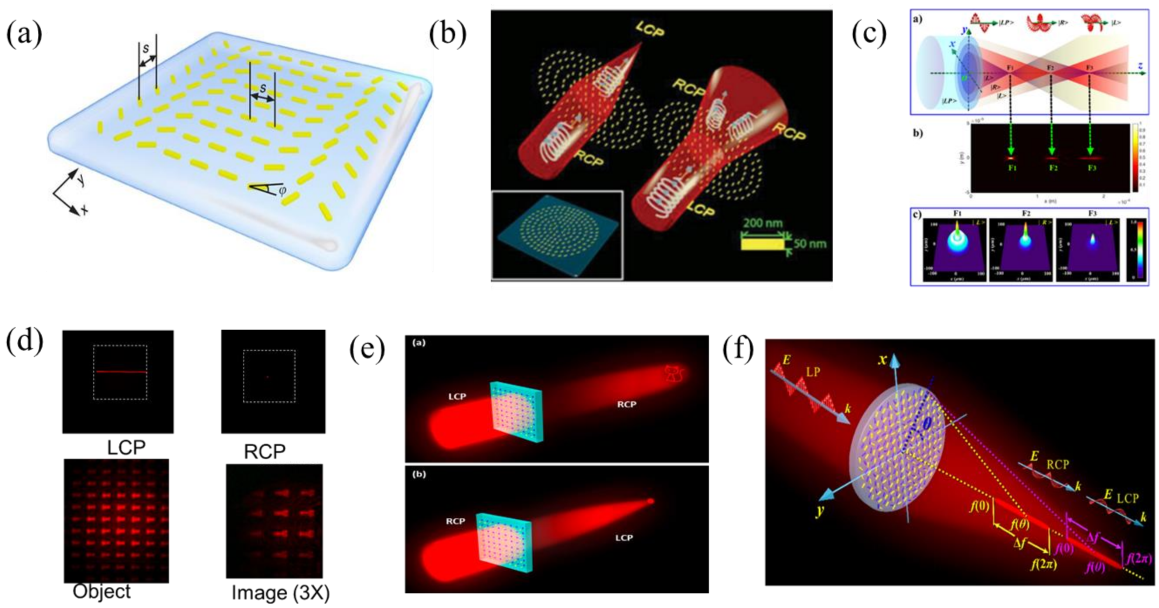

Figure 1. Various ultrathin metalenses. (a) Dual-polarity cylindrical metalens; (b) Dual-polarity circular metalens; (c) Longitudinal multi-foci metalens for circularly polarized light; (d) Multifunctional metasurface lens for imaging and Fourier transform; (e) Metasurface device with helicity-dependent functionality; (f) Multifunctional light sword metasurface lens.

In comparison with traditional lenses, which are typically realized by controlling the surface topography, metalenses are designed based on the abrupt phase change at the interface within a deep-subwavelength range, therefore they can decrease the thickness and volume of the lenses, along with a series of new functionalities which are not even possible for the traditional lenses, such as multiple functionalities [6-13]. In 2012, we developed the first dual-polarity lens[6] in the visible range based on the nanorods with spatially variant orientation (see Figure 1a). For the RCP incident light shining on the metalens, the LCP scattered light in the transmission side forms a bright focal line. However, with the LCP incident light, the RCP scattered light is diverged and leaves a dim background. The reason lies in the fact that the phase profile of the scattered light is conjugated versus the swap of the incident light helicity. Besides the one-dimensional (1D) focusing by the cylindrical lens, the reversible 3D focusing[7] is realized, and its imaging property is experimentally demonstrated by using the T-shaped aperture array as the target object(see Figure 1b). If three sublenses with different focal lengths f_1, f_2, and f_3 are integrated, a multi-foci lens (Figure 1c) can be formed[8]. The sublenses contributing to f_1 and f_3 are designed to work under the LCP incident light, while the sublens corresponding to f_2 works for the RCP incident light. Therefore, the crosstalk between these focal points can be decreased. Such multi-foci lens can be used in particle manipulation, imaging, and quantum information processing. The concept of dual-polarity lens can be further extended to realize a multifunctional lens, which works as a cylindrical (spherical) lens for the RCP (LCP) incident light [9]. Two separate metasurfaces are firstly designed based on the phase functions of the positive cylindrical lens and the negative spherical lens, which are then merged to form the multifunctional lens (Figure 1d). The multifunctional metasurface cannot only include two phase functions with rigorous mathematical function, but also two arbitrary phase functions (see Figure 1e) [10]. Depth of focus is one of important parameters for an imaging system, which determines the range of change for the position of focal plane and image plane. Extending depth of focus of lens has attracted a lot of attention due to its practical applications. Various methods have been proposed to produce an optical element with long depth of focus. Light sword optical elements (LSOEs) are distinguished by angular variation of the optical power since every infinitesimal angular sector has its own focal length, leading to the independence of their optical power range with respect to the pupil's diameter. These devices are typically made by fabricating a transparent substrate at different depths to yield a desired phase profile in the transmitted light. However, LSOEs lack rotational symmetry and exhibit a junction, rendering their fabrication extremely difficult. Furthermore, the sharp edge may hinder their applications in system integration since they should be handled with extreme care, which increases the difficulty level for system assembly. Although diffractive optical elements have the advantage of being relatively flat, their fabrication process is not suitable for the light sword devices since they are highly susceptible to fabrication errors, especially at a point where a big phase change jump is required. To tackle the technical fabrication challenge in LSOEs, we propose and experimentally demonstrate a facile metasurface approach (Figure 1f) to develop multifunctional light sword metasurface lens [11]. Driven by the compact, lightweight, yet high-performance optical systems, in the last several years, researchers have reported various approaches to realize ultrathin optical elements based on metalenses, which can alter the light propagation in an efficient and convenient way. Unfortunately, these designs suffer from strong chromatic aberration, making them unsuitable for precise imaging of objects with multiple colours. The first achromatic metalens that allows achromatic imaging in the visible range was developed by Wang et al. [12] The high index of GaN leads to the formation of optical modes similar to standing waves found in Fabry–Pérot resonators. By altering the width and length of the nanofin, the dispersion of these modes can be changed while keeping the phase accumulation of the light the same. Recently, this work was extended to metalens array for achromatic light-field imaging by Lin et al. [13].

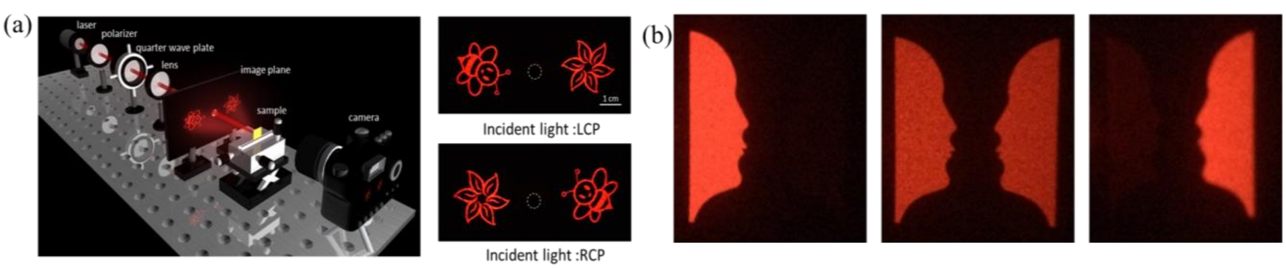

Figure 2. (a) Helicity multiplexed broadband metasurface holograms; (b) Geometric phase generated optical illusion.

2.2 Metasurface holograms

A hologram is the recorded interference pattern of the scattered light, which produces an amplitude hologram through which the scattered wavefront is directly recorded through the intensity of the interference pattern. If the intensity variations in the interference pattern is interpreted into the phase variation, a phase hologram can be obtained which increases the brightness of the image. With the rapid development in metasurfaces and the unprecedented capabilities of manipulating light in a desirable manner by imparting local and space-variant abrupt phase change, the conventional concept of what constitutes an optical hologram device continues to evolve. We reported the realization of three dimensional (3D) holography [14] by using metasurfaces consisting of subwavelength metallic nanorods with spatially varying orientations. As the phase can be controlled locally at each subwavelength unit cell by the rod orientation, metasurfaces represent a new route towards high-resolution on-axis 3D holograms with wide field of view. In addition, the undesired effects of twin images and multiple diffraction orders usually accompanying holography are eliminated. The experimental demonstration of visible frequency metasurface holograms with broadband optical response is a significant challenge to the single layer metallic nanorods due to the high plasmonic loss and difficulties in high-uniformity nanofabrication. To address these challenges, we proposed and experimentally demonstrated a helicity multiplexed metasurface hologram (see Figure 2a) [15] capable of achieving high image quality and high efficiency in the visible and near infrared spectrum. The metasurface hologram features the combination of two sets of hologram patterns operating with opposite incident helicities. A 16-level phase metasurface in the reflection mode is realized by patterning sub-wavelength metallic nanorods with spatially varying orientation on the SiO_2 interlayer and the ground gold plane**.** The metasurface is designed to display two symmetrically distributed off-axis images with high fidelity and a 64.7° field of view that are interchangeable by controlling the helicity of the input light. The demonstrated switchable metasurface hologram with its high performance in image quality, efficiency and bandwidth, represent a major advance in performance compared with previously demonstrated devices with polarization multiplexed functionalities. Our work broadens the general applicability and opens avenues for future applications with functionality-switchable optical devices. An optical illusion, such as "Rubin's vase", is caused by the information gathered by the eye, which is processed in the brain to give a percept that does not tally with a physical measurement of the stimulus source. Traditional optical illusions are typically realized by using specific visual tricks, i.e., complicate graphic design, or under extreme natural environment such as mirages, meaning that they are mainly demonstrated in macroscopic scale. How to generate an additional visual image based on the same ultrathin metasurface device without its closely related phase profile, which can be considered as an optical illusion, has not been demonstrated. For the first time, we experimentally demonstrated an approach to realize the optical illusion based on a metasurface (see Figure 2b) [16]. We take the vase-face drawing that Edgar Rubin described as an example for demonstration. "Rubin faces" are realized by the geometric phase profile induced by the metasurface consisting of metallic nanorods on the top and metallic film at the bottom with the dielectric layer sandwiched between them. Upon the illumination of linearly polarized light, "Rubin's vase" is perceived without mapping the corresponding phase profile onto the metasurface. The demonstrated metasurface devices have shown high performance in optical illusion generation with high efficiency and broad bandwidth. Our result not only provides an intuitive demonstration of the figure-ground distinction that our brains make during the visual perception, but also opens an avenue for new applications related to encryption, optical patterning, and information processing.

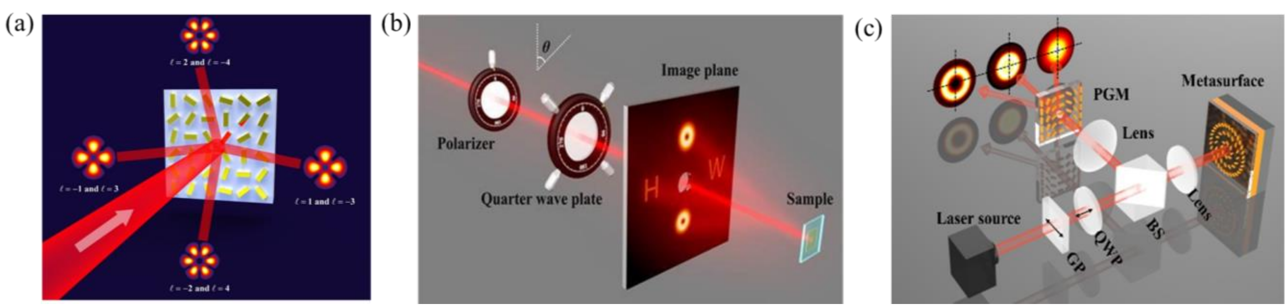

Figure 3. (a) Multichannel polarization-controllable superpositions of orbital angular momentum states; (b) Multichannel metasurface for simultaneous control of holograms and twisted light beams; (c) Vector vortex beam generation with a single plasmonic metasurface.

2.3 Orbital angular momentum (OAM) manipulation

Light beam can carry not only spin angular momentum (SAM), but also orbital angular momentum (OAM). A striking difference between the SAM and OAM is the range of allowed values. SAM can only have two values, $\pm\hbar$ per photon, expressed as left or right circular polarization. OAM has an unbounded value of $\ell\hbar$ per photon, e.g., $\ell = 0,\ \pm1,\ \pm2,\ \pm3......$. Despite many approaches and methods have been proposed to generate the OAM beams, these systems could not be straightforwardly downsized, preventing from widespread applications in integrated optics.

Metsurfaces can not only be utilized to generate the desirable OAM states, but also provides a flexible way to manipulate the superposition of two OAM states, or more in a multichannel manner. Moreover, the limitations of poor resolution of the spatial light modulator, low damage threshold of the q-plate still need to be overcame for practical applications. Nanofabrication advances have enabled the development of metasurfaces capable of controlling the wavefront of the incident light in the subwavelength domain. By spatially adjusting the geometric parameters of unit cell of metasurface, one can generate and control the OAM at will. We proposed and demonstrated a metasurface approach to realize polarization-controllable multichannel superpositions of OAM states (see Figure 3a)with various topological charges[17]. Under the illumination of right-handed circularly polarized light, four OAM states are generated at the same time. By manipulating the polarization state of the incident light, different OAM superpositions are realized in different channels. Owing to its capabilities of arbitrary engineering of phase at nanoscale, metasurface shows great potential in system integration and device miniaturization. For example, we also showed a metasurface device with tunable functionalities including polarization-controllable hologram generation and superposition of orbital angular momentums (see Figure 3b) [18]. Light is characterized by amplitude, phase, and polarization. Besides phase, metasurface can also manipulate the polarization profile, which further expands its capabilities for various applications, such as vector beams. We reported a reflective-type plasmonic metasurface which can generate a vector vortex beam (see Figure 3c) [19]. In this work the vector vortex beams are obtained from the superposition of two circularly polarized components which are the converted parts when the incident light is reflected from the metasurface.

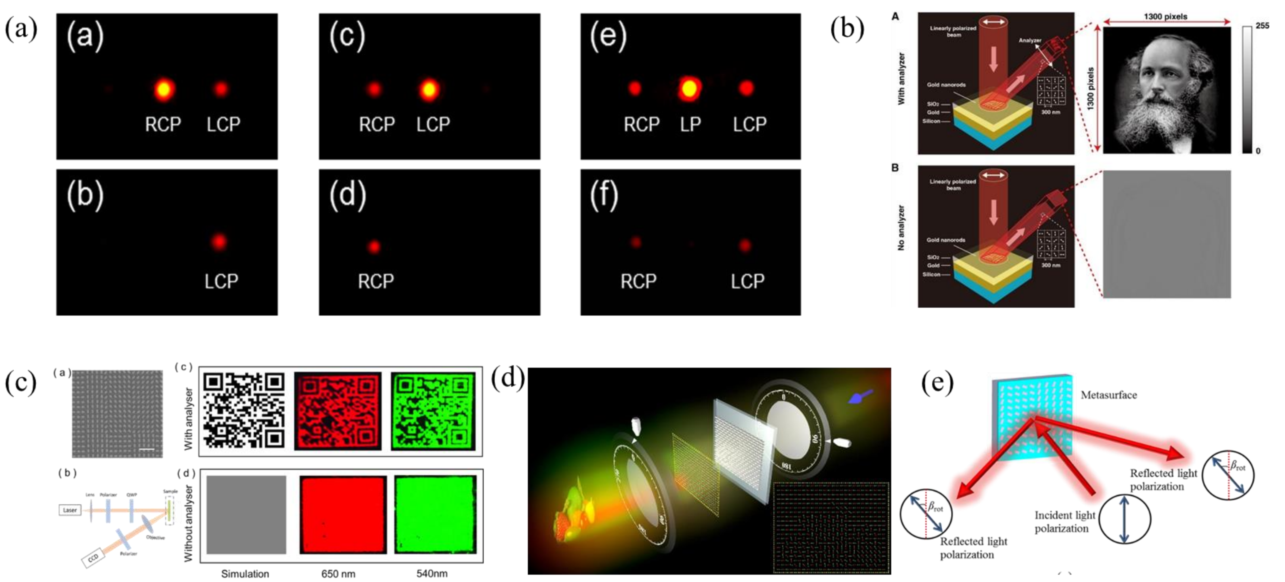

Figure 4. (a) Metasurface for characterization of the polarization state of light; (b) High-resolution grayscale image hidden in a laser beam; (c) Optical metasurface generated vector beam for anti-counterfeiting; (d) Polarization encoded color image embedded in a dielectric metasurface; (e) Plasmonic metasurface for optical rotation.

2.4 Polarization detection and manipulation

Like amplitude and phase, polarization is a fundamental property of light, whose spatial distribution can be used to record, process and store information. The miniaturization of measurement systems currently used to characterize the polarization state of light is limited by the bulky optical components used such as polarizers and waveplates. We experimentally demonstrated a simple and compact approach to measure the ellipticity and its handedness of the polarized light using a phase gradient metasurface (see Figure 4a) [20]. Based on the measured intensities of the anomalously refracted LCP and RCP light, the experimental values of the ellipticity and handedness of the incident light agree very well with predicted values. This work has showed remarkable potential to address major issues typically associated with the current polarization measurement systems, by virtue of its simplicity, miniaturization, compactness and broadband nature. Optical metasurfaces have shown unprecedented capabilities in the manipulation of the light's polarization profile, providing an unusual approach for image encryption. A novel metasurface platform has been demonstrated to hide an image into the polarization profile of a light beam (see Figure 4b). In order to overcome the present technical limitation of resolution and fundamental challenge of arbitrary polarization manipulation, we propose and experimentally demonstrate that, by precisely manipulating the spatially variant polarization states of a laser beam with an ultrathin metasurface, we can hide a high-resolution image within a laser beam. Recently, we have developed a metasurface platform to arbitrarily manipulate the polarization profile of a light beam to encode various types of images, including a high-resolution grayscale image [21], a quick response (QR) code (see Figure 4c) [22] and a color image (see Figure 4d) [23]. To hide the portrait of James Clark Maxwell, a single reflective metasurface is used to continuously manipulate the superposition of two beams with opposite circular polarization states. The reflective metasurface consists of a gold ground layer, a silicon dioxide (SiO_2) spacer layer, and a top layer of gold nanorods. The generated structured light has a very specific polarization in the light beam, thus the electromagnetic field oscillates differently for different parts of the beam. In order to visualize the hidden image in the polarization topology of the laser beam, we reveal the grayscale of the image by using an analyzer (linear polarizer). In doing so, we do not directly observe the spatially-variant polarization profile of the laser beam but rather indirectly confirm its existence through the intensity profile (grayscale image) behind the analyzer. Figure 1 shows the simulation and experiment results. Because the theoretical amplitude of the two beams are exactly the same, no image is observed in the beam without the aid of the analyzer. The experimental result indicates that the image-hidden functionality is unambiguously realized. Similarly, a QR code can also be hidden in the polarization profile of a light beam. We also demonstrate a metasurface platform for simultaneously encoding color and intensity information into the wavelength-dependent polarization profile of a light beam. Unlike typical metasurface devices in which images are encoded by phase or amplitude modulation, the color image here is multiplexed into several sets of polarization profiles, each corresponding to a distinct color, which further allow polarization-modulation induced additive color mixing. This unique approach features the combination of wavelength selectivity and arbitrary polarization control down to a single subwavelength pixel level. Currently, there are fundamental or technical challenges to further reduce the thickness of the optical elements to generate desirable polarization rotation with broadband and high efficiency. For example, the circular dichroism in naturally occurring chiral materials (such as quartz) is very weak, so a minimum optical path length must be available in order to reach a desired rotation range, making the devices very bulky. Although the combination of plasmonics and magneto-optics can enhance the polarization rotation, the rotation angle through optically thin material is not large enough for practical application. To address these challenges, we experimentally demonstrated a novel approach capable of rotating the polarization plane of the linearly polarized light in the visible and near infrared spectrum (see Figure 4e) [24].

3. CONCLUSION

Traditional optical elements are based on refraction, reflection or diffraction of light and the wavefront shaping relies on light propagation over distances much larger than the wavelength to shape wave fronts. At the interface of a metasurface, wave front shaping is accomplished within a distance much smaller than the wavelength of light beam, thus providing new opportunity to develop ultrathin devices that are easy to integrate into compact platforms. Understanding and controlling the phase and polarization between light and nanostructures are fundamental to science and technology development. Optical metasurfaces have gained considerable interests due to their unprecedented capabilities for the modulation of amplitude, phase and polarization at subwavelength scale. Using the technology and experimental expertise that we already have, we can further push the boundaries of this technology to achieve more novel functionalities. For example, the emergent metasurfaces have provided a new design methodology for ultrathin (less than light wavelength) metalenses, offering unlimited potential to engineer the optical properties on demand for imaging. Metalenses have revolutionized lens design and fabrication and have the potential to replace bulky refractive lenses using the same fabrication technology as computer chips. In comparison with conventional lens technology, metalenses have unique properties such as multifunctionality, aberration control, dispersion engineering, and ease of system integration and optical alignment. A multifunction metadevice can integrate multiple functionalities into one device while preserving their independent functionalities. The polarization-controlled imaging can help us see the invisible under demanding environments (detectors are blind to polarization).

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