



Geometric metasurface for simultaneously detecting polarization state and incident angle

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Abstract: Polarization and incident angle are the two fundamental properties of electromagnetic (EM) waves, which can be used to record, store and process information. Thus, the detection of polarization state as well as incident angle of EM waves plays an important role in photonic applications. However, current techniques in detecting the fundamental properties of EM waves are limited to detect only one physical dimension (e.g., polarization) of EM waves. Here we propose and experimentally demonstrate an approach for simultaneously detecting polarization and incident angle of terahertz (THz) waves based on a geometric metasurface platform. By transforming the rotational symmetry associated with the off-axis incident light to the translational symmetry, the quadratic phase profile is encoded into a geometric metasurface, leading to a single focal point with wide field of view (WFOV) for detecting the polarization and incident angle of THz waves. The incident angle can be revealed just by detecting the translational distance from the center of the focal plane, while the polarization state is achieved through the reconstructed Stokes parameters using the intensity and phase of the single focal point. This unique approach enabling multi-dimensional detection may open a new avenue for designing multifunctional THz devices and integrated systems.

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1. Introduction

Polarization is one of the intrinsic properties of EM waves that can be traditionally controlled/generated by specular reflection, birefringence, and dichroism. The manipulation of polarization can possess a plethora of applications including polarization navigation [1], polarization imaging [2], optical displays [3] and quantum communication [4]. In addition, a variety of matter information is associated with polarization, and thus, polarization can be also applied to identify and detect material composition [5,6], morphology [7], and structural information of macroscopic matter [8]. Therefore, not only the generation/manipulation of polarization but also the detection of polarization is of great importance due to the versatile applications. In fact, the polarization information of EM waves can be obtained from two traditional polarization detection methods (or polarimetry systems), i.e., time-division measurement [9] and simultaneous measurement [10]. Time-division measurement for detecting polarization is realized by rotating polarizers and wave plates, while simultaneous measurement is dependent on the detection of corresponding polarization component simultaneously. However, the conventional polarimetry systems are inevitably limited to the complex optical paths and the bulky size, which hinder the development of miniaturized and integrated optical systems.

Metasurfaces [11,12], as the two-dimensional counterpart of metamaterials, consisting of planar antennas with predesigned EM response can accurately tailor the amplitude, polarization and

phase of incident EM waves by abrupt phase changes (at planar antenna interfaces), which provide a flexible and ultra-compact platform for device miniaturization and system integration. Benefiting from the ultrathin nature, easy of fabrication and miniaturized characteristics, metasurfaces have enabled a variety of applications ranging from beam steering [13–15], vortex generation [16–22], polarization conversion [23–26] to metalens [27–34] and holograms [35–40]. Metasurfaces also provide new solutions for polarization detection. For instance, a geometric metasurface encoded with spin-dependent phase gradient has been proposed to deflect left-handed circularly polarized (LCP) and right-handed circularly polarized (RCP) components of the incident optical beam in opposite directions, leading to the detection of chirality and ellipticity of light [41]. A metagrating consisting of three interweaved metasurfaces, where each function as a polarization splitter, has been proposed and designed to analyze an arbitrary state of light polarization by detecting corresponding diffraction intensities [42]. The division of focal plane polarization cameras (DoFp-PCs) was designed by interleaved metasurfaces to split and focus light in three different polarization bases, enabling full Stokes characterization of the state of polarization [43]. Furthermore, metasurface-generated vortex beams have been proposed to reconstruct the full-Stokes parameters of EM waves by the mode purity and multidimensional analysis of the transmitted vortex field [44,45]. In addition, the polarization filter-based Stokes metasurfaces, single-layer metasurface spectrometer, multi-foci metalens-based polarimeter and tightly focusing polarimeter have been proposed to detect the polarization of EM waves [46–49]. However, previous metasurface-based schematics for detecting polarization are mainly dependent on the combination of geometric and propagation phases and interleaved metasurfaces (i.e., multi-focus metalenses used for polarization detection). More seriously, the current techniques in detecting the fundamental properties of EM waves are typically limited to detect only one physical dimension (e.g., polarization) of EM waves. How to reconstruct multiple physical dimensions (e.g., polarization and incident angle) of EM waves by a single metasurface (i.e., a non-interleaved metasurface) is indispensable to develop the miniaturized and integrated optical systems, since incident angle is another degree of freedom for processing and storing information [50].

In this paper, we propose and experimentally demonstrate an approach that can integrate multifunctional detection (i.e., polarization and incident angle) in a non-interleaved geometric metasurface. A WFOV metalens encoded with a quadratic phase profile is designed by transforming the rotational symmetry related to the off-axis incident light to the translational symmetry. Such a metalens with a single focal point enables the unprecedented capability in tolerating the oblique incidence, and the detection of incident angle of EM waves can be reconstructed by detecting the translational distance from the center of the focal plane due to the translation of a linear phase into a spatial shift. In addition, polarization recognition is achieved by detecting the intensity and phase of the single focal point. The integration of multifunctional detection in a single metasurface opens a new window for designing future ultra-compact and multifunctional devices with potential applications in imaging, detection and communications.

2. Design and methods

Figure 1(a) schematically shows a WFOV metalens that can focus the incident THz waves with arbitrary state of polarization (SoP) and angle of incidence into a focal point located at the same focal plane but different spatial positions. Such a metalens consists of dielectric meta-atoms with identical shape but different in-plane orientations (i.e., geometric metasurface). It can focus the LCP and RCP components (of incident waves) together, and thus, the incidence of THz waves with arbitrary SoP can be focused into a focal point. In addition, the position of the focal point is related to the angle of incidence, and the incident angle can be revealed by detecting the translational distance from the center of the focal plane, as shown in Fig. 1(b). The Stokes parameters of incident THz waves can be reconstructed by extracting the intensity and phase of the focal point, as shown in Fig. 1(c).

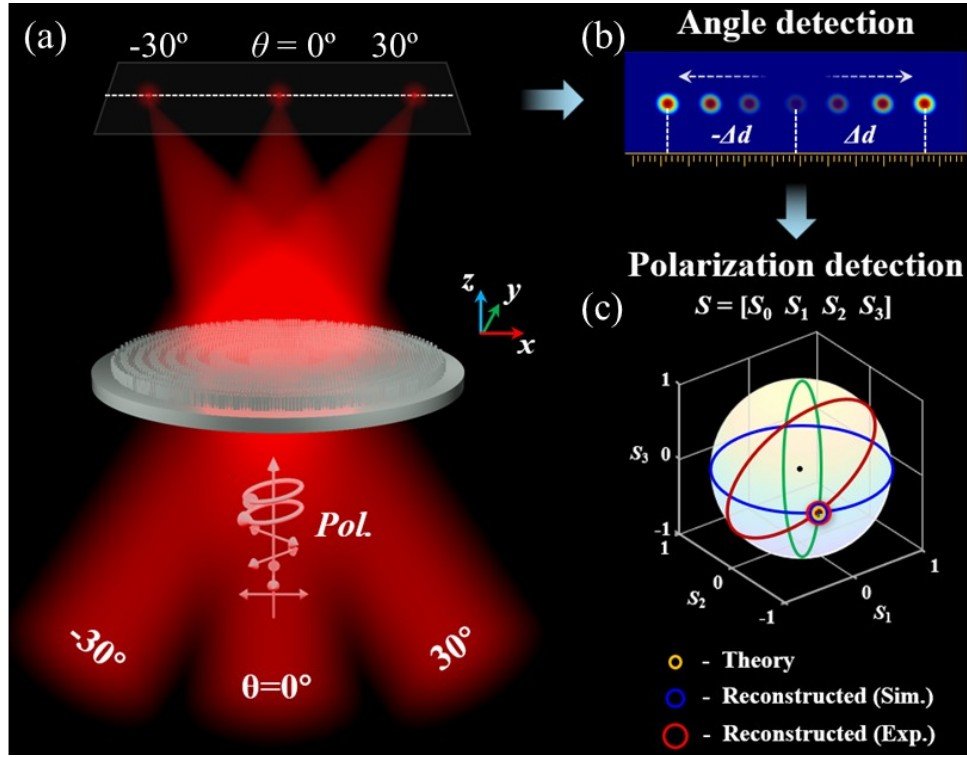


Fig. 1. (a) Schematic of a WFOV metalens for simultaneously detecting polarization and incident angle of THz waves. (b) The detection of incident angle based on the translational distance of the focal point. (c) The theoretical and reconstructed Stokes parameters on the surface of the Poincaré sphere.

A super-symmetric lens enabling the WFOV capability [51] can be obtained by encoding the quadratic phase profile as follows:

$$\varphi = \frac{2\pi}{\lambda} \frac{r^2}{2f}, \quad (1)$$

where λ is the wavelength of incident waves. f is the focal length, while r is the radial distance to the center of the lens.

For the oblique incidence of THz waves (in the xz plane) with an incident angle of θ to the normal axis of the lens, the quadratic phase transforms a linear phase into a spatial shift that is deduced as follows:

$$\varphi' = \frac{\pi}{\lambda f} (x^2 + y^2) - \frac{2\pi}{\lambda} x \sin \theta = \frac{\pi}{\lambda f} [(x + f \sin \theta)^2 + y^2] + \frac{\pi f \sin^2 \theta}{\lambda}, \quad (2)$$

where $\frac{\pi f \sin^2 \theta}{\lambda}$ is a constant. Therefore, the oblique incidence will induce a spatial shift (i.e., $f \sin \theta$) for the focal point. Therefore, the detection of incident angle (of THz waves) is moved to detect the translational distance from the center of the focal plane (see Fig. 1(b)). This quadratic phase profile enables precise polarization state and incidence angle quantification across wide angular ranges.

For the generation of a focal point located at $(0, 0, f)$ under the illumination of LCP THz waves, the phase requirement of a geometric metalens can be expressed as

$$\varphi_{LCP} = \frac{2\pi}{\lambda} \frac{r^2}{2f}. \quad (3)$$

Accordingly, under the illumination of RCP THz waves, the phase requirement for generating a focal point at $(0, 0, f)$ is governed by

$$\varphi_{RCP} = -\frac{2\pi}{\lambda} \frac{r^2}{2f}. \quad (4)$$

Therefore, a geometric metalens with the spin-decoupled function that can simultaneously focus LCP and RCP components of incident THz waves can be realized by encoding the following phase requirement:

$$\varphi_{total} = \arg[\exp(i\varphi_{LCP}) + \exp(i\varphi_{RCP})]. \quad (5)$$

This sum-of-exponential approach will focus both the LCP and RCP light (therefore robust to the polarization state) and not lead to the ambiguities due to the properties of geometric phase³⁰.

To verify the simultaneous detection of incident angle and SoP, we design a geometric metalens consisting of silicon-based (with $\varepsilon = 11.9$, $\mu = 1$, $\sigma = 2.5 \times 10^{-4}$ S/m) meta-atoms with identical shape but different in-plane orientations, as shown in Figs. 2(a) and 2(b). Each meta-atom is optimized with the structural parameters as: $L = 99 \mu\text{m}$, $W = 35 \mu\text{m}$, and $H_1 = H_2 = 500 \mu\text{m}$. The period of each meta-atom is designed as $P = 120 \mu\text{m}$. Figure 2(c) shows the transmission spectra and phase difference of a dielectric meta-atom under the illumination of transverse electric (TE) and transverse magnetic (TM) THz modes. When a meta-atom is illuminated with a TE THz beam, the transmission at 0.6 THz (Fig. 2(c) red curve) is 95%, while the transmission of TM THz mode is also 95% at 0.6 THz (Fig. 2(c) blue curve). The phase difference between TE and TM modes is about π . Therefore, the designed meta-atom is a quasi-perfect half waveplate. The metasurface is fabricated with the phase profile following Eq. (2) by rotating the meta-atoms, showing the priority (robustness to polarization and convenience to design) to the traditional approaches. The optical image of our fabricated metalens and the corresponding phase profile (encoded in such a metalens) are shown in Figs. 2(d) and 2(e). In experiment, a near-field scanning THz microscopy system (NSTMs) is constructed to detect the electric-field intensity and phase distributions after the metalens. A THz tip behind the THz source (mounted on a rotatable stage to control the incident angle of the incident THz waves) is mounted on a three-dimensional translation stage to detect the corresponding electric-field distribution by scanning/shifting the THz tip. The sample (e.g., metalens) is fixed while the THz tip is mounted on a three-dimensional (3D) translation stage to collect electric-field and phase distributions.

3. Results and discussion

To demonstrate the dual-detection function of our proposed approach, a metalens encoded with the predesigned phase profile (Eq. (5)) is designed and measured with the electric-field intensity distributions and SoP characteristics shown in Fig. 3. The working frequency of our designed metalens is designed at 0.6 THz, and it consists of 100×100 meta-atoms (Fig. 2(d)). The focal length is designed as $f = 5 \text{ mm}$. The incident angle of THz waves can be revealed by detecting the spatial shift of the focal point, while the polarization of incident waves is identified by extracting the electric-field intensity distributions ($|E_x|^2$ and $|E_y|^2$) and the phase difference between E_x and E_y . After that, the corresponding polarization state can be revealed by calculating the Stokes

parameters as follows:

$$\begin{aligned} S_0 &= |t_x|^2 + |t_y|^2 \\ S_1 &= |t_x|^2 - |t_y|^2 \\ S_2 &= 2|t_x||t_y|\cos(\varphi_d) \\ S_3 &= 2|t_x||t_y|\sin(\varphi_d) \end{aligned} \quad (6)$$

where t_x and t_y are the transmission coefficients of x -polarized (E_x) and y -polarized (E_y) electric

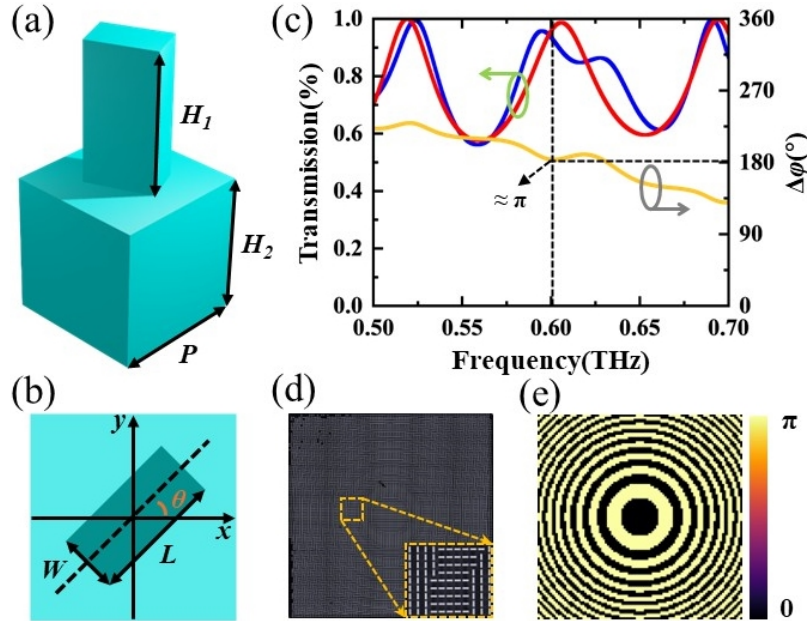


Fig. 2. (a) and (b) Schematics of a dielectric meta-atom in a geometric metalens. (c) Transmission spectra and phase difference of a dielectric meta-atom upon the illumination of TE and TM modes. (d) and (e) The optical image of metalens (d) and the corresponding phase profile (e) encoded in such a metalens.

fields. The field intensity of transmitted THz waves is represented by S_0 , while the x/y -polarized electric fields are identified as S_1 . Linearly-polarized (LP) components in the diagonal and antidiagonal directions can be revealed by S_2 , and the circularly polarized components are determined by S_3 . In addition, φ_d is the phase difference between two orthogonal (E_x and E_y) electric field components.

As shown in Fig. 3(a) for the normal incidence of x -polarized THz waves, our designed metalens can focus the incident waves into a focal point located at (0, 0, 5 mm). The simulated and measured electric-field intensity distributions in the focal plane are shown in Figs. 3(b) and 3(c). A focal point located at the center of the focal plane is observed, demonstrating the incident angle of 0° . By extracting the two orthogonal (E_x and E_y) electric field intensities and the corresponding phase difference (between E_x and E_y) in the focal plane, the Stokes parameters can be obtained based on Eq. (6). As shown in Figs. 3(d) and 3(e), the polarization of the incident THz waves is an x -polarized beam. It should be noticed that the measured results agree well with the simulated/theoretical results except for a slight discrepancy that can be attributed to the fabrication and test errors (inhomogeneous THz source and intrinsic noise of the experiment system). When the incident THz waves are switched into a y -polarized beam and normally impinge onto the same metalens, a focal point located at the center of the focal plane is generated,

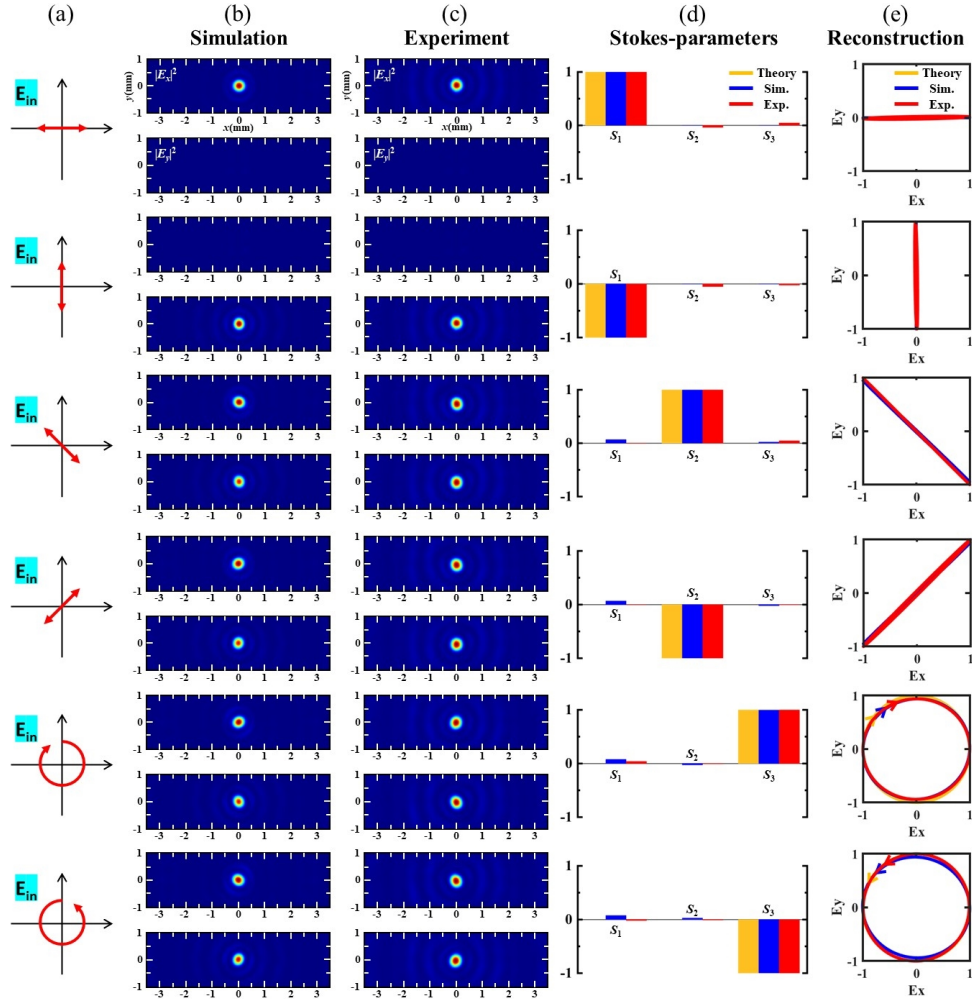


Fig. 3. Simulated and measured results of a metalens for simultaneously detecting polarization and incident angle under the normal ($\theta = 0^\circ$) illumination of THz waves. (a) Six states of polarization (x-polarized/y-polarized/antidiagonally-polarized/diagonally-polarized/LCP/RCP SoP) of the incident THz waves. (b) Simulated electric-field intensity distributions ($|E_x|^2$ and $|E_y|^2$) under the illumination of the six states of polarization. (c) Measured electric-field intensity distributions ($|E_x|^2$ and $|E_y|^2$) under the illumination of the six states of polarization. (d) The theoretical, simulated and measured Stokes parameters extracted from the focal point. (e) The theoretical, simulated and measured polarization ellipses.

which demonstrates the normal incidence of THz waves. In addition, the Stokes parameters inversely verify the y-polarized THz incidence. For the normal incidence of anti-diagonally-polarized and diagonally-polarized THz waves, a focal point (with $|t_x| \approx |t_y|$) located at the center of the focal plane is obtained. The simulated and measured Stokes parameters (with $S_2 \approx \mp 1$) also reveal the anti-diagonally/diagonally-polarized SoP. Under the normal illumination of LCP/RCP THz waves, the focal point (with $|t_x| \approx |t_y|$ and $\varphi_d \approx \pm \frac{\pi}{2}$) located at the center of the focal plane is also observed, and the revealed states of polarization are matched well with that of the incident

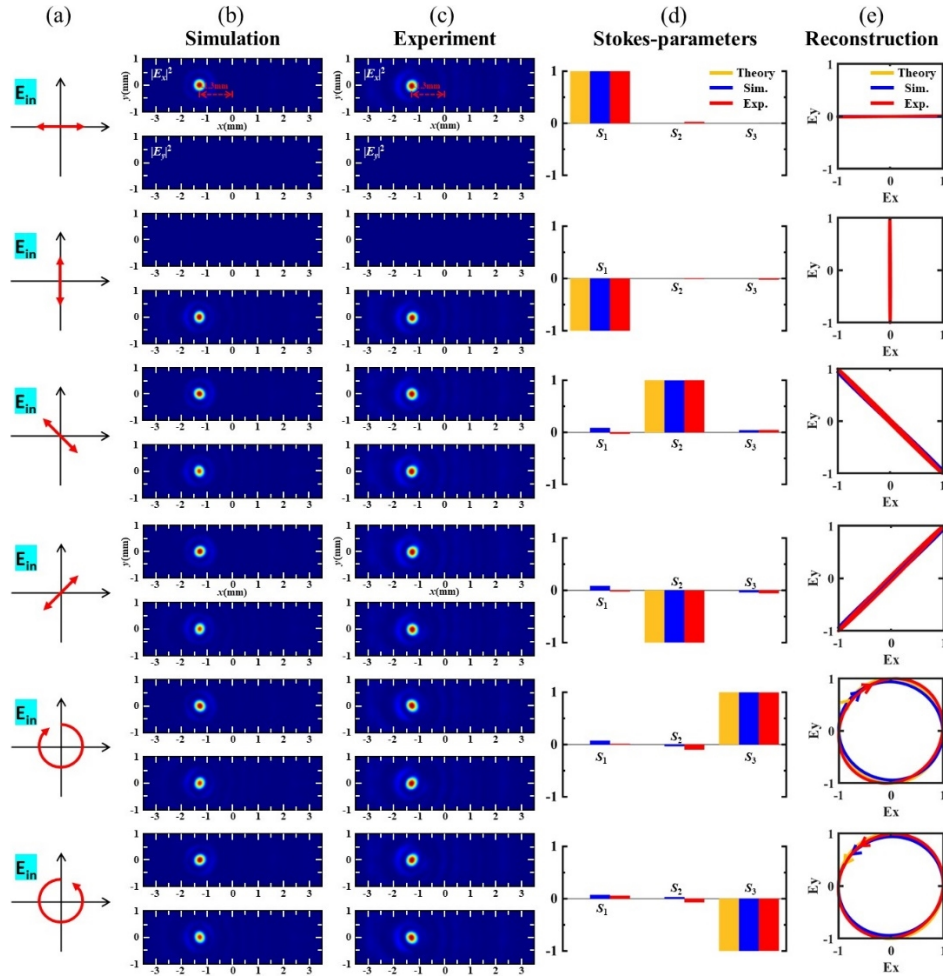


Fig. 4. Simulated and measured results of a metalens for simultaneously detecting polarization and incident angle under the oblique (with incident angle of $\theta = 15^\circ$) illumination of THz waves. (a) Six states of polarization (x-polarized/y-polarized/anti-diagonally-polarized/diagonally-polarized/LCP/RCP SoP) of the incident THz waves. (b) Simulated electric-field intensity distributions ($|E_x|^2$ and $|E_y|^2$) under the illumination of the six states of polarization. (c) Measured electric-field intensity distributions ($|E_x|^2$ and $|E_y|^2$) under the illumination of the six states of polarization. (d) The theoretical, simulated and measured Stokes parameters extracted from the focal point. (e) The theoretical, simulated and measured polarization ellipses.

THz waves. The simulated and measured phase difference between two orthogonal (E_x and E_y) electric field components is also supplied in [Supplement 1](#) section 1.

To further demonstrate the dual-detection function, a THz beam lies in the xz plane with incident angle of $\theta = 15^\circ$ (to the normal axis) impinges on the same metalens (shown in Fig. 2(d)) with the electric-field intensity and revealed SoP shown in Fig. 4. For the oblique incidence of an x-polarized THz beam, this metalens can focus the incident waves into a focal point (Fig. 4(a)). However, the focal point is not located at the center of the focal plane but located at (-1.3 mm, 0, 0) or (-1.3 mm, 0, 0) in simulation or experiment, leading to a spatial shift in the x -axis. When the polarization of incident THz waves is switched into y-polarized, anti-diagonally polarized,

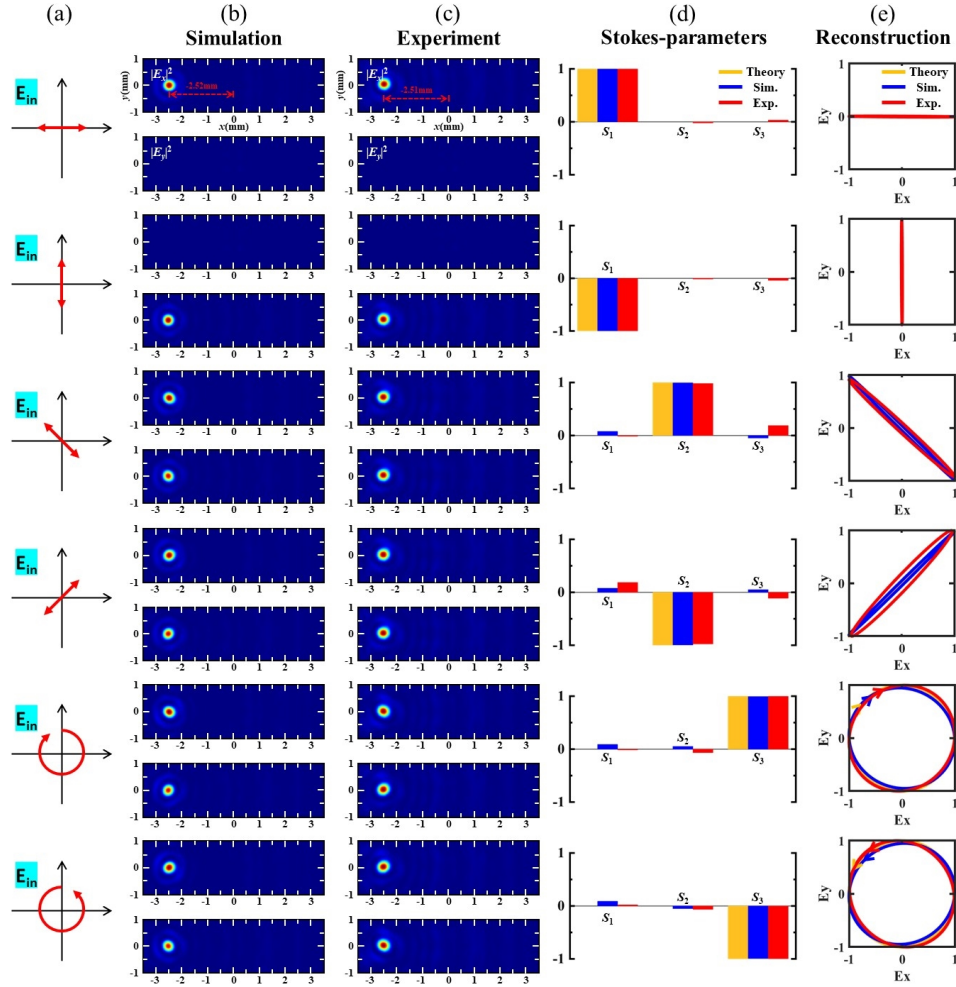


Fig. 5. Simulated and measured results of a metalens for simultaneously detecting polarization and incident angle under the oblique (with incident angle of $\theta = 30^\circ$) illumination of THz waves. (a) Six states of polarization (x-polarized/y-polarized/anti-diagonally-polarized/diagonally-polarized/LCP/RCP SoP) of the incident THz waves. (b) Simulated electric-field intensity distributions ($|E_x|^2$ and $|E_y|^2$) under the illumination of the six states of polarization. (c) Measured electric-field intensity distributions ($|E_x|^2$ and $|E_y|^2$) under the illumination of the six states of polarization. (d) The theoretical, simulated and measured Stokes parameters extracted from the focal point. (e) The theoretical, simulated and measured polarization ellipses.

diagonally polarized, LCP, or RCP SoP, a focal point can be observed and it is also located at (-1.3 mm, 0, 0) or (-1.3 mm, 0, 0) in simulation or experiment. The efficiencies of the metalens are provided in [Supplement 1](#) section 3, which are limited to a maximal value of 50%.

This demonstrates that the oblique incidence of THz waves is translated into the spatial shift of the focal point. Therefore, we can detect the incident angle of THz waves by measuring the translational distance from the center of the focal plane. As shown in Figs. 4(b) and 4(c), the spatial shift in simulation/experiment is -1.3/-1.3 mm. According to the Eq. (2), the revealed incident-angle (based on $\Delta d = f \sin \theta$ where Δd is the spatial shift) of THz waves is $15.1^\circ/15.1^\circ$ which agrees well with the predesigned incident angle. The detection of polarization (of the incident THz waves) can be also implemented by extracting the intensity and phase difference between two orthogonal LP components (i.e., E_x and E_y). The Stokes parameters extracted from the focal point and SoP and the corresponding polarization ellipses (see Figs. 4(d) and 4(e)) demonstrate that the SoP can be revealed by our designed metalens under the oblique incidence of THz waves. In addition, the simulated and measured phase difference (under the oblique incidence) between two orthogonal (E_x and E_y) electric field components are also supplied in [Supplement 1](#) section 1.

To demonstrate the designed metalens enabling a larger FoV and the dual-detection function, a THz beam with oblique incident angle of 30° (to the normal axis) is shining on the same metalens. Figure 5 shows the electric-field intensity distributions and revealed SoP extracted from the focal point. For the oblique incidence of THz waves with six SoP (Fig. 5(a)), a focal point can be generated based on the spin-decoupled metalens. Because of the oblique incidence, the focal point with a significant departure from center of the focal plane is observed and located at (-2.51 mm, 0, 0)/(-2.52 mm, 0, 0) in simulation/experiment, as shown in Fig. 5(b). Therefore, the revealed incident angle of incident THz waves is $30.13^\circ/30.26^\circ$ (in simulation/experiment), which is matched with the predesigned angle of incidence. The detection of SoP of incident THz waves is illustrated by the Stokes parameters (that are extracted from intensity and phase) and the polarization ellipses, as shown in Figs. 5(d) and 5(e). The revealed SoP is agreed well with that of the incident THz waves, demonstrating the detection of SoP with wide-angle incident waves. The simulated and measured phase difference (under the oblique incidence) between two orthogonal (E_x and E_y) electric field components are also supplied in [Supplement 1](#) section 1. In addition, the simulated and measured results of a metalens for simultaneously detecting polarization and incident angle under the oblique illumination (with incident angle of $\theta = -15^\circ, -30^\circ$) of THz waves, are given in [Supplement 1](#) section 2.

4. Conclusion

In summary, we have proposed and experimentally demonstrated a method that can focus the incident THz waves with arbitrary SoP and incident angle into a focal point just using the pure geometric phase modulation. A geometric metalens encoded with the quadratic phase profile that can simultaneously focus the two orthogonal helical-components of incident THz waves with large FOV has been designed, fabricated and experimentally tested. Our designed metalens can be applied to simultaneously detect SoP and angle of the incident THz waves: SoP can be revealed by extracting the intensity and phase of two orthogonal LP components (i.e., E_x and E_y), while the incident angle can be obtained just by detecting the translational distance from the center of the focal plane. This unique and robust approach can be extended to design multifunctional THz devices with versatile applications in detecting, imaging and communications.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplemental document. See [Supplement 1](#) for supporting content.

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