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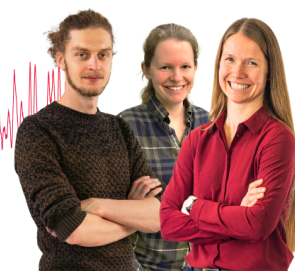
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ABSTRACT

Benefiting from the unprecedented capacity in manipulating wavefront of light waves, metalens can realize unusual functions that are very difficult or impossible to achieve with conventional lenses. However, the current techniques for designing a metalens are limited to obtain polarization-dependent or polarization-independent focal points, preventing its versatile applications in modern optics. Here, we propose and experimentally demonstrate an approach that can focus the left-handed circularly polarized and/or right-handed circularly polarized components of terahertz (THz) waves to simultaneously generate polarization-dependent and polarization-independent focal points. First, a metalens is designed to obtain two focal points where the intensity of one focal point can be controlled by controlling polarization of incident THz waves, while the intensity of another focal point is fixed under the illumination of THz waves with arbitrary polarization. Second, a metalens with intensity-tunable multiple focal points and an intensity-fixed focal point is experimentally demonstrated. Third, the single to multifocal imaging (i.e., reconfigurable imaging) can be realized using the designed metalens without the aid of reconfigurable materials. In addition, a framework for mimicking logic gates is designed based on the proposed metalens. This robust approach for designing metalens with reconfigurable focal points may open a window in developing multifunctional devices with potential applications in imaging, sensing, and communications.

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Metasurfaces, which are the two dimensional counterpart of metamaterials, enable the unprecedented capacity in accurately controlling the intensity, phase, and polarization of electromagnetic (EM) waves, leading to the development of ultra-compact, miniaturized, and integrated optical components with versatile functionalities.^{1,2} Metasurfaces are usually consisting of planar meta-atoms with size-variable or identical shapes and different in-plane orientations that can be deliberately designed to manipulate EM waves at subwavelength resolution. Additionally, the manipulation of EM waves is only dependent on the abrupt phase changes at the meta-atom/air interfaces, and thus, the thickness of metasurfaces is much smaller than the wavelength of incident EM waves, providing an ideal candidate for device miniaturization and system integration. Benefiting from the ultrathin

nature and easy of fabrication characteristics, metasurfaces have shown a plethora of applications including generalized Snell's law,^{3,4} the spin Hall effect,^{5–9} polarization converters,^{10–15} vortex beams,^{16–20} holograms,^{21–26} and quantum sources.^{27–30}

Metalens, which is one of the most typical devices of metasurfaces, enables a variety of applications ranging from imaging,³¹ virtual/augmented reality headsets,³² phone cameras,³³ sensors to display.³⁴ For example, a dual-polarity plasmonic metalens based on helicity-dependent phase discontinuities for circularly polarized light has been designed and experimentally demonstrated to generate helicity-controllable real and virtual focal planes, leading to magnified and demagnified imaging.³⁵ An all-dielectric metalens consisting of high-aspect-ratio titanium dioxide meta-atoms was further proposed and

fabricated, and the diffraction-limited focusing was achieved at visible wavelengths with high focusing efficiency.³⁶ By eliminating the chromatic aberration over a continuous wavelength, broadband achromatic metalenses have been designed and experimentally demonstrated with various applications in achromatic focusing and beam deflection,³⁷ achromatic imaging,³⁸ and full-color light-field imaging.³⁹ In addition, multi-foci metalenses generating a variety of focal points with different states of polarization were proposed and designed to form customized vectorial focal curves that can be dynamically modulated by controlling the linear polarization direction of the incident light.^{40–43} By further combining metalens and metallic gratings together, the Janus metalens can be realized, leading to the directional focusing and asymmetric imaging.^{44–46} Recently, the multi-foci division of focal plane polarization cameras were designed and could split and focus light in different polarization bases, leading to the application in detecting the full Stokes characterization of incident light waves.⁴⁷ However, the current metalenses are limited to generate polarization-dependent or polarization-independent focal point(s). The simultaneous generation of polarization-dependent and polarization-independent focal point(s) based on a single metalens (especially for geometric phase-based metalens without the using of active materials) is strongly necessary for developing reconfigurable applications.

In this work, we conceptually propose an approach that can focus both or one of the helical components of the incident terahertz (THz)

waves into multiple polarization-dependent and polarization-independent focal points. A metalens that can generate one polarization-dependent focal point and one polarization-independent focal point is designed and experimentally demonstrated. The single to multifocal imaging (i.e., reconfigurable imaging) is further demonstrated by using this designed metalens. Furthermore, a metalens with intensity-tunable multiple focal points and an intensity-fixed focal point is designed, and the intensity-tunable focal points and an intensity-fixed focal point are verified. In the end, the logic gates platform is proposed and constructed based on our proposed metalens. Although this approach is demonstrated in the THz band, it can be promoted to the other electromagnetic band through the similar method.⁴⁸ The unique approach for designing metalens with reconfigurable focal points by controlling polarization of incident THz waves can be further extended to design ultra-compact and multifunctional devices with applications in imaging, display, communications, and more advanced photonics devices.

Figure 1(a) schematically shows the operating principle of a metalens that can generate polarization-dependent and polarization-independent focal points under the illumination of linearly polarized (LP) THz waves. This metalens consists of anisotropic meta-atoms with identical shape but different in-plane orientations, and thus, the manipulation of incident THz waves is dependent on the pure geometric phase. For the incident LP THz waves, this metalens can focus

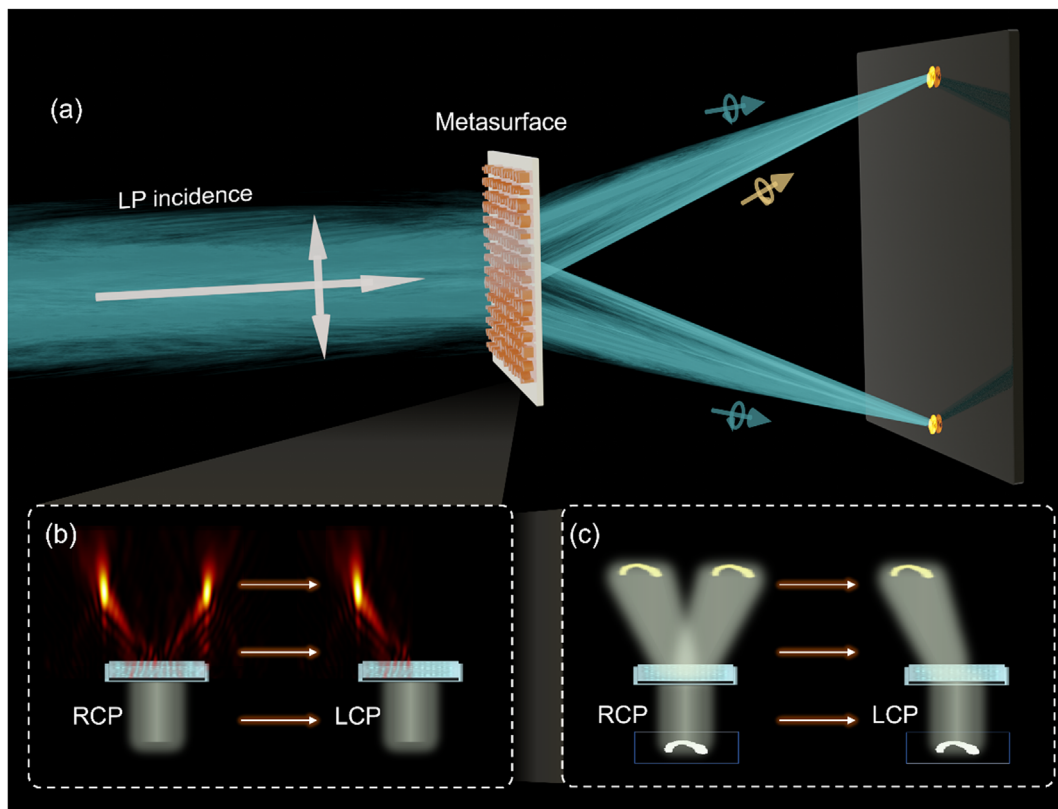


FIG. 1. (a) Schematic of a metalens that can generate polarization-dependent and polarization-independent focal points. (b) A metalens for generating two focal points and one focal point under the illumination of LCP and RCP THz waves. (c) Schematic of the single to multifocal imaging based on our designed metalens.

the two helical components [i.e., both left-handed circularly polarized (LCP) and right-handed circularly polarized (RCP) components] into a focal point, while it also can focus only one helical component (i.e., LCP or RCP components) into a focal point, leading to the polarization-dependent and polarization-independent focal points. As shown in Fig. 1(b) for the incidence of RCP THz waves, two symmetrically distributed focal points are generated, while only one focal point is observed (and located at the right half space of the focal plane) under the illumination of LCP THz waves. Therefore, a polarization-independent focal point located at the right half space of the focal plane and a polarization-independent focal point located at the left half space of the focal plane are generated based on our designed metalens. This metalens enables the reconfigurable imaging functionality, as shown in Fig. 1(c). Therefore, under the illumination of LCP/RCP THz waves, the single to dual-foci imaging can be realized just by controlling the polarization of incident THz waves.

For focusing the LCP/RCP component of incident THz waves into a focal point located at (x_f, y_f, f) , the quadratic phases are employed to enhance the field of view for the metalens, which can be expressed as follows:⁴⁹

$$\varphi_{LCP}(x, y) = \frac{2\pi}{\lambda} \frac{r^2}{2f}, \quad (1)$$

$$\varphi_{RCP}(x, y) = -\left(\frac{2\pi}{\lambda} \frac{r^2}{2f}\right), \quad (2)$$

where r is the radial distance to the lens center, λ is the working wavelength, and f is the focal length. Equations (1) and (2) are the phase profiles to, respectively, generate a polarization-dependent focal point.

To generate a polarization-independent focal point, the phase requirement for the metalens can be represented as

$$\varphi_{CP}(x, y) = \arg[\exp(i\varphi_{LCP}) + \exp(i\varphi_{RCP})]. \quad (3)$$

To obtain intensity-fixed and intensity-tunable focal points, a metalens should encode the phase profile as

$$\varphi_{total}(x, y) = \arg[\exp(i\varphi_{CP}^i) + \exp(i\varphi_{LCP}^j)], \quad (4)$$

where $\varphi_{CP}^i = \arg[\exp(i\varphi_{LCP}^i) + \exp(i\varphi_{RCP}^i)]$ and $\varphi_{LCP}^i = -\varphi_{RCP}^i = \frac{2\pi}{\lambda} \frac{(x-x_i)^2 + (y-y_i)^2}{2f}$, $\varphi_{LCP}^j = \frac{2\pi}{\lambda} \frac{(x-x_j)^2 + (y-y_j)^2}{2f}$. It should be noted that an intensity-fixed focal point is located at (x_i, y_i, f) , while another intensity-tunable focal point is located at (x_j, y_j, f) . The sum-of-exponential approach will not lead to the ambiguities due to the properties of geometric phase, which have been demonstrated for designing the multi-foci metalens.³⁵

To demonstrate the above-mentioned functionalities, geometric metasurfaces-based metalens consisting of anisotropic meta-atoms with identical shape but different in-plane orientations is designed as shown in Fig. 3(a). The meta-atoms are fabricated from intrinsic silicon with a relative permittivity of $\epsilon_r \approx 11.7 + 0.015i$ at the operational frequency, exhibiting negligible absorption losses ($\kappa \approx 0$). The

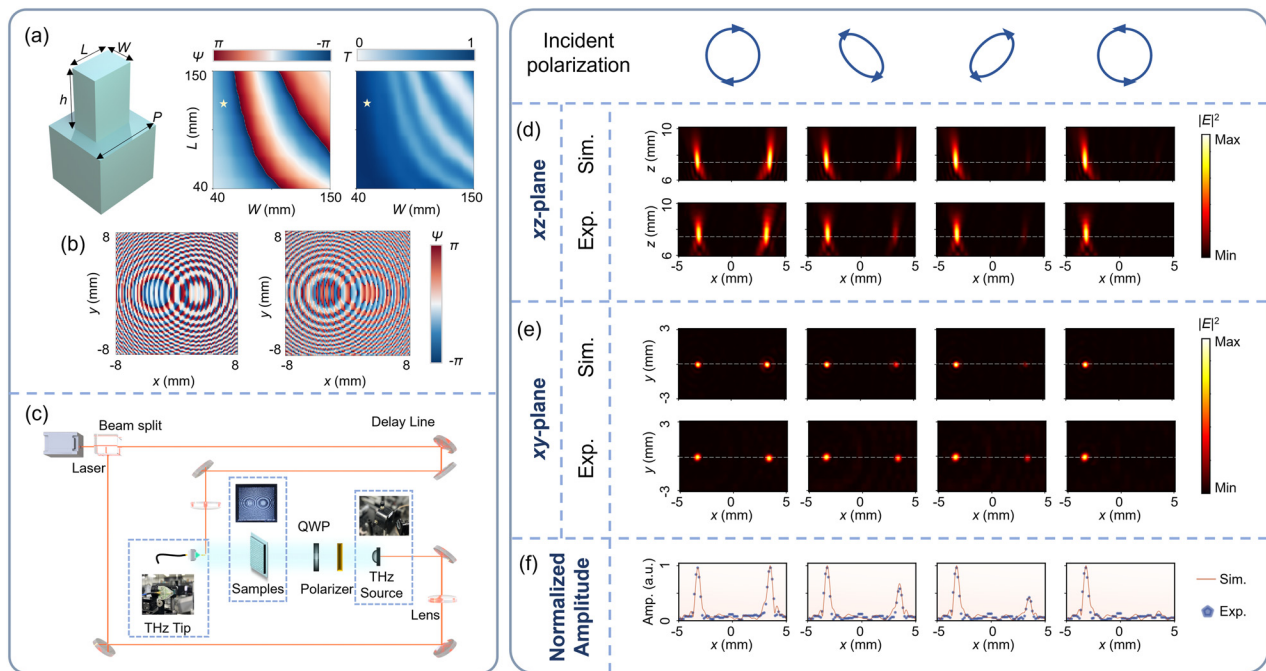


FIG. 2. (a) Schematic of a meta-atom in the designed metalens and the simulated phase maps and transmittance as a function of lateral dimensions of L and W . (b) The calculated phase distributions of designed metalens (for generating intensity-fixed and intensity-tunable focal points) under the illumination of RCP and LCP THz waves. (c) Schematic of experiment setup. (d) Simulated and measured electric-field intensity distributions in the xz plane after the designed metalens upon the incidence of THz waves with polarization switched from RCP to LCP. (e) Simulated and measured electric-field intensity distributions in the xy plane after the designed metalens upon the incidence of THz waves with polarization switched from RCP to LCP. (f) Normalized intensity at $y=0$ with red lines for simulations and blue stars for measurements.

simulated phase maps and transmittance as a function of lateral dimensions of L and W are shown in Fig. 3(a). The optimized structural parameters are $P = 160 \mu\text{m}$, $L = 120 \mu\text{m}$, and $W = 50 \mu\text{m}$. The height of meta-atom and substrate is $500 \mu\text{m}$. The metalens consists of 110×110 meta-atoms, and the working frequency is 0.6 THz . Since the designed metalens can generate intensity-fixed and intensity-tunable focal points, the phase distributions (for this metalens) are different under the illumination of RCP and LCP THz waves.

A near-field scanning terahertz time-domain spectroscopy microscopy system in Fig. 2(c) is constructed with the assistance of B-THz Co., Ltd.⁵⁰ to detect the diffractive field after the sample/metalens. A femtosecond laser pulse with a central wavelength of 780 nm is divided into two parts: one part of this laser beam is coupled into a single-mode fiber (with a length of 5 cm), and then, it impinges onto a THz tip to further generate the photon-generated carriers for detection. The other part of laser beam is guided and focused onto the THz photoconductive antenna to excite the THz radiation, which is interacted with the sample. The THz tip is mounted on a three-dimensional translation stage to collect electric-field after the sample, and the spatial resolution of the THz tip is $3 \mu\text{m}$. In experiment, the metalens is fixed, while the THz tip is moved step-by-step (with a step size of $75 \mu\text{m}$) to scan the field distributions. The polarized THz wave is generated with the commercial polarizer and the quarter-wave plate, which ensures that the polarization extinction ratio exceeds 98%.

As a feasibility study, a metalens that can generate one polarization-dependent focal point and one polarization-independent focal point is designed and experimentally demonstrated in Figs. 2(d)–2(f). According to Eq. (4), the phase profile encoded into a metalens can focus both the LCP and RCP components of incident THz waves into (x_f, y_f, f) , while only the incidence of LCP component can be focused and located at (x_f, y_f, f) , leading to the intensity-fixed and intensity-tunable focal points, respectively. The focusing locations are defined as $(-3.2 \text{ mm}, 0, 7.5 \text{ mm})$ for the polarization-independent focal point and $(3.2 \text{ mm}, 0, 7.5 \text{ mm})$ for the polarization-dependent focal point. As shown in Fig. 2(c) (top left) for the incidence of RCP THz waves, two focal points are generated and symmetrically distributed in the focal plane. The measured electric-field intensity distributions after the metalens also show two symmetrically distributed focal points [bottom left in Fig. 2(c)], which are matched well with the simulated results. A slight discrepancy in field distributions between simulation and experiment can be attributed to the fabrication and experimental errors. The corresponding electric-field intensity distributions in the xy -plane are shown in Fig. 2(e) (top left and bottom left). These two focal points show almost the equivalent intensity distributions in the focal plane, as demonstrated in Fig. 2(f) (left figure). When the incidence is switched into RECP (right-handed elliptically polarized), LECP (left-handed elliptically polarized), and LCP THz waves, the left focal point is still observed with the fixed intensity

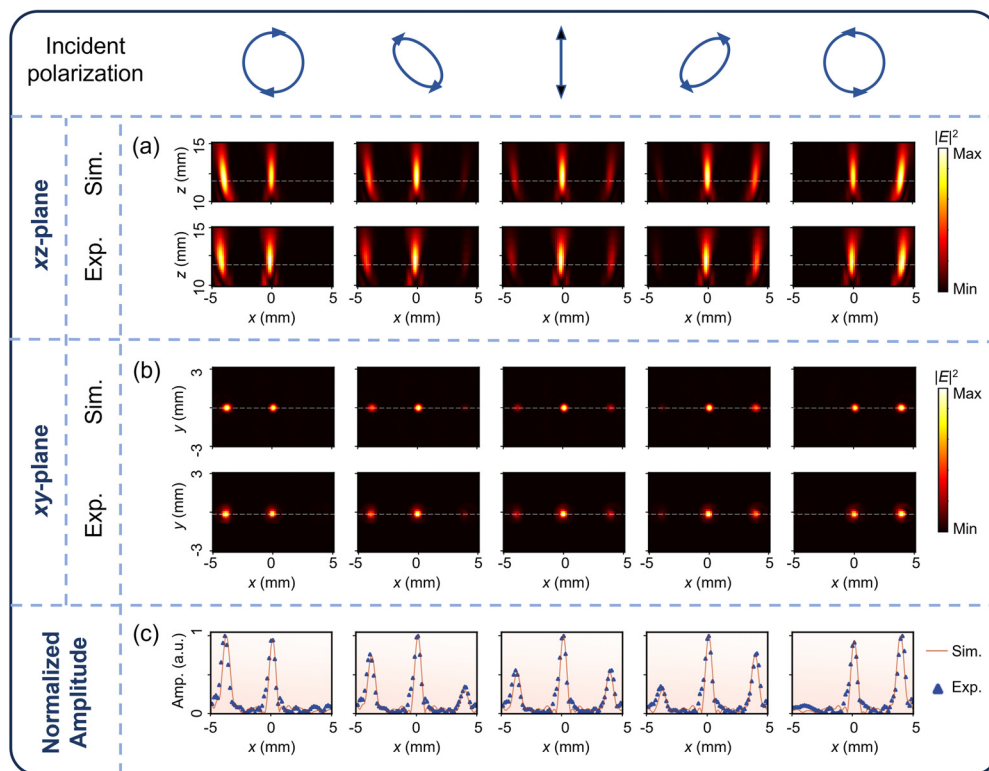


FIG. 3. A metalens for generating intensity-tunable multiple focal points and an intensity-fixed focal point. (a) Simulated and measured electric-field intensity distributions in the xz plane after the designed metalens under the incidence of THz waves with polarization switched from RCP to LCP. (b) Simulated and measured electric-field intensity distributions in the xy plane after the designed metalens under the incidence of THz waves with polarization switched from RCP to LCP. (c) Normalized intensity at $y = 0$ with red lines for simulations and blue stars for measurements.

distributions, while the right focal point is gradually disappeared (i.e., none of a focal point can be observed in the right half space) with the tunable intensity distribution. The electric-field intensity distributions in the xz -plane [Fig. 2(d)] and xy -plane [Fig. 2(e)] demonstrate that the left focal point with fixed intensity is always observed in the left half space, while the intensity of the right one is gradually decreased and disappeared for the LCP incidence. In addition, the axial depth for these focal spots is approximately 1.1 mm in experiment. The simulated and measured intensity distributions at $y = 0$ mm also verify the polarization-independent and polarization-dependent characteristics of our designed metalens.

To further demonstrate the versatility and high performance of our proposed approach, a metalens that can generate intensity-tunable multiple focal points and an intensity-fixed focal point is designed and experimentally demonstrated in Fig. 3. In this situation, the phase requirement encoded in the metalens is governed by

$$\varphi_{total}(x, y)' = \arg[\exp(i\varphi_{CP}^i) + \exp(i\varphi_{LCP}^i) + \exp(i\varphi_{RCP}^k)], \quad (5)$$

$$\text{where } \varphi_{CP}^i = \arg[\exp(i\varphi_{LCP}^i) + \exp(i\varphi_{RCP}^i)], \quad \varphi_{LCP}^i = -\varphi_{RCP}^i \\ = \frac{2\pi}{\lambda} \frac{(x-x_i)^2 + (y-y_i)^2}{2f}, \quad \varphi_{LCP}^j = \frac{2\pi}{\lambda} \frac{(x-x_j)^2 + (y-y_j)^2}{2f}, \quad \text{and} \quad \varphi_{RCP}^k = -\frac{2\pi}{\lambda} \\ \times \frac{(x-x_k)^2 + (y-y_k)^2}{2f}.$$

The focusing locations are defined as (0 mm, 0, 12.5 mm) for the polarization-independent focal point and (± 4 mm, 0, 12.5 mm) for the polarization-dependent focal points.

As shown in Fig. 3(a) (top and bottom left) for the incidence of RCP THz waves, this metalens can generate two focal points located at (-4 mm, 0, 12.5 mm) and (0, 0, 12.5 mm). The corresponding

intensity distributions in the focal plane [Fig. 3(b)] also show the two focal points. The simulated and measured intensity distributions at $y = 0$ illustrate that these two focal points have the identical intensity, as shown in Fig. 3(c). For the incidence of THz waves with polarization switched from RECP, LECP to LCP, the intensity of the focal point located at (-4 mm, 0, 12.5 mm) is gradually decreased and disappeared for the LCP incidence, while the focal point located at (4 mm, 0, 12.5 mm) is gradually increased and achieves the maximal intensity distributions under the illumination of LCP incidence, demonstrating the intensity-tunable multiple focal points. In other words, we can accurately control the intensity ratio between these two focal points. It should be noted that the focal point located at (0, 0, 12.5 mm) is unimpeded for the incidence of THz waves with different polarizations, enabling an intensity-fixed focal point. In addition, the experimental axial depth of the polarization-independent focal point and polarization-dependent focal point is 1.51 and 2.21 mm, respectively.

Our designed metalens not only can manipulate the incident THz waves into polarization-dependent and polarization-independent focal points but also enables the unprecedented capability in reconfigurable imaging, as shown in Fig. 4. The metalens that can focus incident THz waves into one polarization-independent focal point and one polarization-dependent focal point is utilized to demonstrate the reconfigurable imaging. Figure 4(a) shows the schematic for the experimental detection of the imaging.

Considering both the non-paraxial effects and the interference between two images, a $4f$ system is established to demonstrate the reconfigurable imaging—the distance between the object and focusing lens and the focal length of this focusing lens are 10 mm, while the

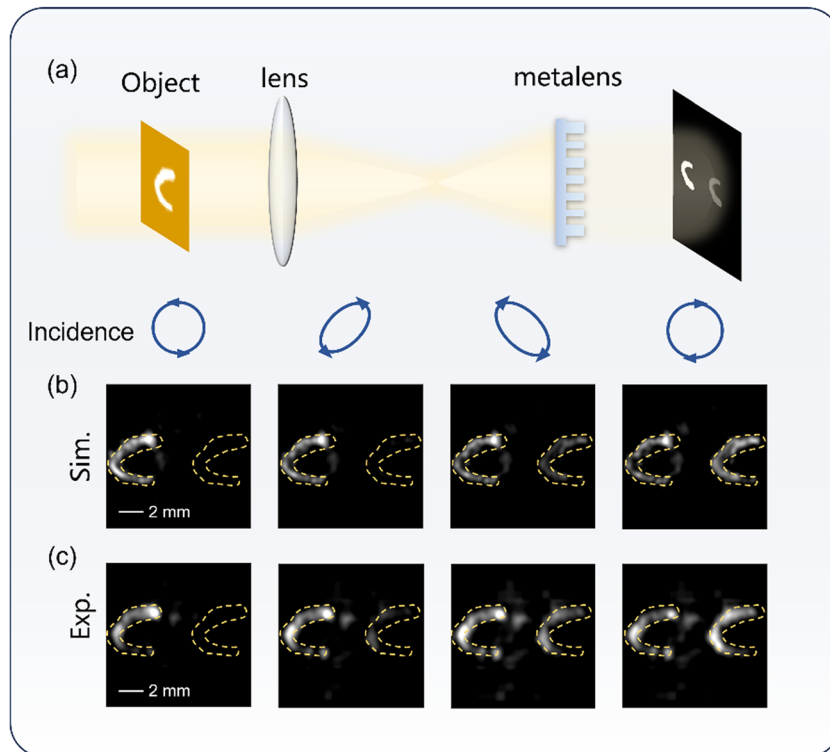


FIG. 4. Metalens for reconfigurable imaging. (a) Schematic of reconfigurable imaging. (b) and (c) Simulated (b) and measured (c) electric-field intensity distributions for the single to multifocal imaging.

image distance and focal length of the metalens are 7.5 mm. As shown in Fig. 4(b) (left) for the incidence of LCP THz waves, the imaging with one “C” is observed in the image plane. The measured result in Fig. 4(c) (left) also shows a C-shaped imaging in the image plane. When the incidence with polarization switched from LCP, LECP to RECP and RCP, another C-shaped imaging located at the right half image plane is increasingly apparent, leading to two C-shaped images with approximately identical intensity distributions upon the incidence of RCP THz waves. The detailed quantitative imaging metrics of the imaging system can be found in Sec. 3 of the [supplementary material](#).

Our proposed metalens can be further extended to mimic the logic gates by combining with phaser devices, as shown in Fig. 5. A x -polarized THz beam and a y -polarized THz beam with phase difference of $\Delta\Psi_0 = \pm 0.5\pi$ simultaneously arrive at the two phaser devices, and each phaser device can independently add a phase shift $\Delta\varphi$ to the x -polarized and y -polarized THz waves. The predesigned recognition-region in the right side (the white dashed box) is selected to mimic the logic gates, while the left side region represents the connection signal that mimics the handshake process in the communication protocol (e.g., TCP/IP) to ensure data reliability. For the “XNOR” gate, the phase difference $\Delta\Psi_0 = 0.5\pi$. Without phase shift for the x -polarized and y -polarized THz waves, the x -polarized and y -polarized THz components can be considered as the code “0 0”; then, the selected region is illuminated with a focal point after the x -polarized and y -polarized THz components passed through the

metalens, as shown in Fig. 5(b). Then, the input codes of “0 1,” “1 0,” and “1 1” can be obtained just by adding the phase shifts of $0/\pi$, $\pi/0$, and π/π into the x/y -polarized component. The selected region is not illuminated for the input codes of 0 1 and 1 0, while it is illuminated for the input code of 1 1 [Fig. 5(b)]. In contrast, for the “XOR” gate, the phase difference $\Delta\Psi_0 = -0.5\pi$, the selected region is illuminated for the input codes of 1 0 and 0 1, while it is not illuminated for the input codes of 1 1 and 0 0, as shown in Fig. 5(c). Furthermore, we also demonstrate that the NAND and NOR gates can be simultaneously achieved with the multi-foci metalens (see Sec. 4 of the [supplementary material](#)).

In summary, we have proposed and demonstrated an approach to design metalenses that can focus the incident THz waves into polarization-dependent and polarization-independent focal points. A metalens that can generate one polarization-dependent focal point and another polarization-independent focal point was designed and experimentally verified. Then, we extend this method into the design of a metalens for generating intensity-tunable multiple focal points and an intensity-fixed focal point. The single to multifocal imaging has been demonstrated based on our designed metalens. Finally, the metalens for mimicking logic gates has been proposed and numerically demonstrated. This robust approach for designing polarization-dependent and polarization-independent focal points opens a window to develop multifunctional devices with potential applications in imaging, display, and communications.

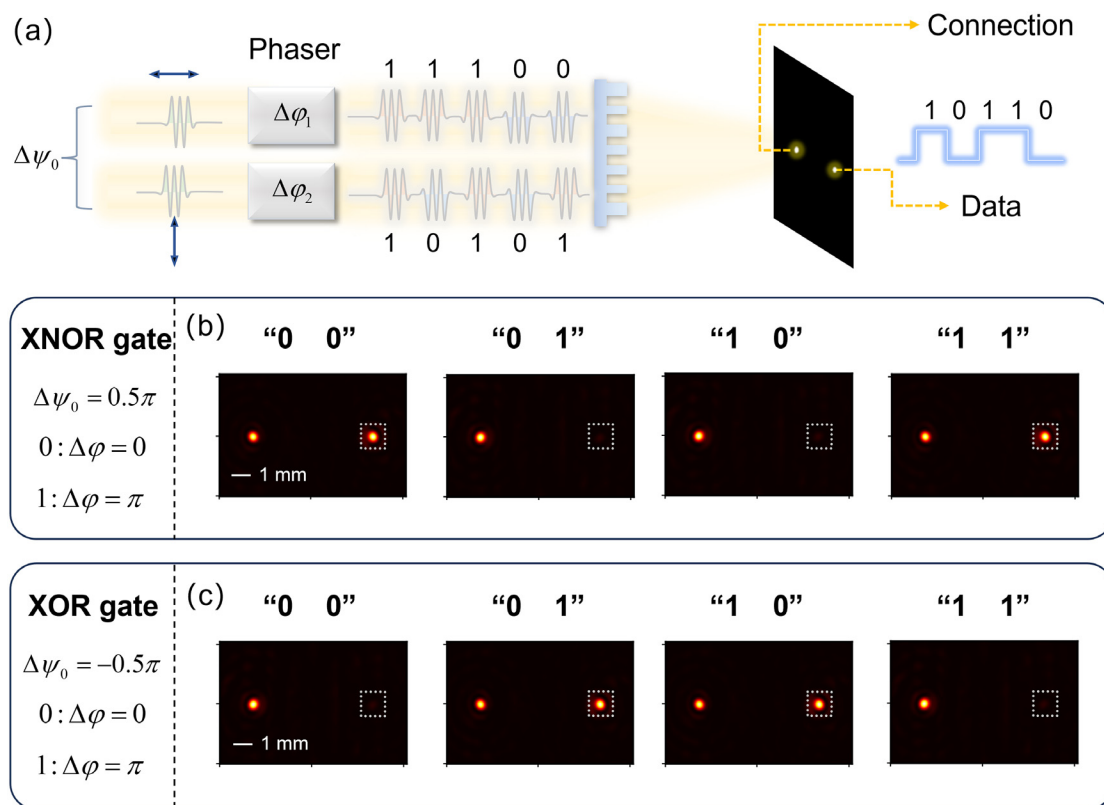


FIG. 5. Metalens for mimicking logic gates. (a) Schematic for the generation of logic gates. (b) Simulated results for “XNOR” gate. (c) Simulated results for “XOR” gate.

See the [supplementary material](#) for (1) sample fabrication; (2) analysis of the efficiency of the proposed metasurfaces; (3) characterization of metrics of the reconfigurable imaging system; and (4) logical gates with the multi-foci metalens.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Yinghao Yuan: Data curation (equal); Funding acquisition (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Ruisi Wang:** Validation (supporting). **Yuanbo Wang:** Writing – review & editing (equal). **Deng Zhang:** Writing – review & editing (equal). **Gaopeng Li:** Validation (supporting). **Zhiyu Tan:** Validation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Xiaofei Zang:** Funding acquisition (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Yiming Zhu:** Funding acquisition (equal); Validation (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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