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ABSTRACT

Traditional spherical lenses are bulky and often the limiting factor for the miniaturization of modern smart devices. Metalenses can break the limitations of traditional spherical lenses, allowing for the development of ultra-thin planar lenses. Here, we experimentally demonstrated metalenses in the mid-infrared spectral range by patterning a germanium wafer using standard nanofabrication processes. Three 6 mm × 6 mm planar lenses operating at 3 μm, 5 μm and 8 μm were fabricated and characterized. The results show that the focusing efficiency of the metalenses reaches 80% and the numerical aperture is as high as ~ 0.8, close to the designed theoretical value. The metalenses are also used to image a lighter fire with a quality comparable to traditional spherical lenses.

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I. INTRODUCTION

Lenses are important optical devices in imaging systems that manipulate the light propagation path by controlling the light refraction angle using curved surfaces. The principle of using curved surfaces to manipulate light results in bulky and expensive lenses widely seen in the market. In the past half century, the development of integrated circuits has been so successful that cheaper and smaller electronic devices (smart phones, for example) are available in large quantity. This successful technological advance leads to two consequences. First, the miniaturization of electron devices is increasingly limited by the bulky lenses, resulting in a strong market force driving for the revolutionary lens technology. Second, advanced fabrication techniques are readily accessible, which allows for the fabrication of nanostructures at large scale. In recent years, a disruptive planar lens technology has been successfully demonstrated in visible to mid-infrared spectrum by manipulating the light propagation path via the control of local refractive indices, instead of surface curvatures, using nano- or micro-structures. For instance, Yang et al. proposed in 2017 a high-efficiency reflective metalens designed for wavelength of 1550 nm. The authors solved the polarization-dependent problem of metalens by utilizing two arrays of nanoblocks to form the super cell. Metalenses designed for wavelengths of around 4 μm, 4.8 μm and 10.6 μm were also demonstrated recently. However, most of the presented mid-infrared metalenses were based on amorphous silicon. Compared to silicon, germanium has an extended mid-infrared transmission window from 2 - 14 μm which is more suitable for applications in IR imaging. In this letter, we demonstrated that similar planar lenses at mid-infrared range can be realized by nano-structuring a germanium (Ge) wafer that is transparent in mid-infrared spectrum. Three 6 × 6 mm² planar lenses operating at 3 μm, 5 μm and 8 μm were designed and fabricated by using Ge nanofin structures distributed in a particular pattern. The performances of these planar lenses are comparable to the traditional Ge lens except that the planar lenses show a relatively strong dispersion.

II. SIMULATIONS AND EXPERIMENTS

Fig. 1(a) shows the schematic of a transmission germanium metalens designed for mid-infrared spectral range. The building blocks of the metalens are high-aspect-ratio germanium nanofins whose basic structure and dimensions are denoted in Fig. 1(b) and (c). A Pancharatnam–Berry-phase (PB phase) metasurface can achieve a full phase control by adjusting the rotation angle of each building block. In case of circular-polarized (CP) normal incidence, the transmitted electric field can be calculated via the operation of Jones Matrix and given by:

\[ E_{\text{LR}} = i(\theta) \cdot \hat{\epsilon}_{\text{LR}} = \frac{t_0 + t_e}{2} \hat{\epsilon}_{\text{LR}} + \frac{t_0 - t_e}{2} e^{i2\theta} \hat{\epsilon}_{\text{RL}}, \]

where \( t_0 \) and \( t_e \) represent the complex transmission coefficients along two directions of nanofin, and \( \hat{\epsilon}_{\text{LR}} = (\hat{\epsilon}_x \pm \hat{\epsilon}_y) / \sqrt{2} \) are the...
FIG. 1. Design and simulations of metalenses. (a) Schematic of the metalens and building blocks. The light is launched from the backside of the substrate. (b) A germanium nanofin on a germanium substrate. (c) Top views of a nanofin with length L, width W and dimensions of a unit cell P × P. The required phase is imparted by rotation of the nanofin by an angle $\theta_{nf}$. (d) Simulated effective index along e axis ($n_e$), o axis ($n_o$) and the resulted phase retardation of an isolated nanofin designed for the wavelength of 5 μm. (e) Simulated focusing efficiency of metalenses designed for the wavelengths of 3, 5 and 8 μm, respectively.

Jones vector of left-handed CP (LCP) or right-handed CP (RCP) light.\cite{16,17} From the second term we can see that a phase shift of $2\theta$ can be achieved for the opposite handedness radiation by rotating the nanofin by $\theta$. To function as a spherical lens in the case of right-handed circularly polarized incident light, the rotation of each nanofin according to their coordinates (x, y) is given by the following equation

$$\theta_{nf}(x, y) = \frac{1}{2} \phi_{nf}(x, y) = \frac{\pi}{\lambda_d} \left( f - \sqrt{x^2 + y^2 + f^2} \right),$$

where $\phi_{nf}$ is the phase profile introduced by rotation of each nanofin, $\lambda_d$ the design wavelength and $f$ the focal length.\cite{7,18,19}

As known that every single nanofin can be considered as a channel of waveguide and exhibit form birefringence.\cite{20,21} As shown in Fig. 1(a) and (b), the incident light is along z-axis and there exist two axes along x- and y-axis denoted as extraordinary axis (e axis) and ordinary axis (o axis), respectively. The electric field polarized along the e axis will have an effective mode index different from the one along the o axis. By adjusting the size of the nanofin we can change the effective index along e axis ($n_e$) and o axis ($n_o$), thus creating a phase retardation so that a nanofin can operate as a wave-plate at certain wavelength. The phase retardation $\Gamma$ caused by a single nanofin is given by Eq. (3).

$$\Gamma = \frac{2\pi L (n_e - n_o)}{\lambda_0},$$

where $n_e$ and $n_o$ are the two effective indices and L is the propagation length in the media.\cite{22,23}

To ensure that our metalens work at their best performance, we need the nanofin to act as a half-wave-plate. We performed MODE simulations using Lumerical on a single germanium nanofin suspended in air to adjust the effective indices along e axis ($n_e$) and o axis ($n_o$). For these simulations, periodic boundary conditions were applied at the x and y boundaries and perfectly matched layers (PML) at the z boundaries. Here we chose the metalens designed for the wavelength of 5μm as an example to illustrate the simulation procedure. As shown in the Fig. 1(d), by tuning the width of germanium nanofin with a fixed length, we can easily find that $n_e$ and $n_o$ change differently as the width decreases, leading to a phase retardation along the two axes for the propagation length of 1.5 μm (nanofin height). The phase retardation increases from 0 to $\pi$ as we decrease the width from 2.5 μm to 550 nm. Other two similar simulations were also applied for nanofins designed at the wavelength of 3 μm and 8 μm. From these simulations we determined the dimensions of the three kinds of nanofins as shown in Table I.

| TABLE I. Specifications of metalenses designed at wavelengths of 3 μm, 5 μm and 8 μm. |
|---|---|---|---|
| W (nm) | L (μm) | H (μm) | P (μm) |
| 3 μm | 427 | 1.5 | 1.3 |
| 5 μm | 550 | 2.5 | 3 |
| 8 μm | 850 | 4 | 2.5 | 5 |
FIG. 2. (a) to (c) Simulated focal spot intensity profile of the metalens designed at (a) 3 μm, (b) 5 μm and (c) 8 μm. (d) to (f) Corresponding vertical cuts of the focal spots of the metalenses, shows their FWHMs = 1.81, 3.02 and 4.81 μm, respectively.

FIG. 3. (a) Photo of a 6×6 mm metalens with a ruler to mark the size. (b) Optical image of the metalens designed at the wavelength of 5 μm. (c) and (d) Close-up SEM micrographs of the fabricated metalenses designed at 8 μm and 3 μm, respectively.
domain (FDTD) simulations can be performed by using Lumerical software to verify the focusing performance of the metalens. We performed FDTD simulations on metalens with different size. When the numerical aperture is fixed, the focal length and the maximum light intensity at the focal spot will linearly increase as the metalens size (area) increases, whereas the focal spot size and focusing efficiency remain constant independent of the metalens size (data not shown here). It is reasonable to assume that these linear and constant properties will maintain when the metalens size increases to macroscopic scale. In this way, we find the simulated focusing efficiency for a metalens that has an area of $6 \times 6 \text{ mm}^2$ and a focal length of 2 mm (NA of 0.832), as shown in Fig. 1(e). Note that we assumed the incident light is launched in the “infinitely” thick germanium substrate. The reflection loss by the germanium wafer surface can be neglected. The focusing efficiencies of metalens designed at the wavelength from 3 $\mu$m to 8 $\mu$m are all around 80%. We show the light intensity profile on the focal plane of each metalens in Fig. 2. The size of each focal spot reaches its diffraction-limit, which is $\frac{\lambda}{2 \pi}$.

Following the aforementioned simulations, three distinct metalenses were fabricated on a double-side polished germanium wafer. The fabrication process is more straightforward in comparison with the TiO$_2$ and metallic metalenses designed for visible range. The electron beam resist ZEP520 (340 nm-thick) was first spin-coated onto the Ge substrate and patterned by electron-beam lithography (EBL, Vistec EBPG-5200) at a dosage of 155 $\mu$C/cm$^2$. We then applied reactive ion etching (RIE) process with optimized parameters based on the recipe for etching silicon ($\text{SF}_6 = 45$ sccm, $\text{C}_4\text{F}_8 = 20$ sccm, $T = 5$ $^\circ$C, $P_{\text{ICP}} = 450$ W, $P_{\text{bias}} = 13$ W, Pressure = 10 mTorr). After that we removed the remaining resist mask and the Ge planar metalens were formed, as shown in Fig. 3(a) and (b). Fig. 3(c) and (d) show scanning electron microscopic (SEM) images of the fabricated metalenses designed for 8 $\mu$m and 3 $\mu$m, respectively.

![Diagram](image_url)
To visualize and investigate the focusing performance of the fabricated metalenses, we set up an optical system as shown in Fig. 4(a). The IR light source is an IR monochromator (Zolix Omni-λ 300i, Beijing, China) that can provide IR monochromatic light in the wavelength range from 1.5 to 10 μm with a wavelength bandwidth of 60 nm. The IR monochromator is integrated with a compact mirror system to output parallel light. It is also equipped with a linear polarizer (OB0011, Fingqi, Inc., Beijing, China) paired with a quarter-wave plate (OB0005, Fingqi, Inc., Beijing, China) to create circularly polarized output from arbitrarily polarized light since the metalenses are designed to operate for circularly polarized light. The output light passes through metalenses from the backside is focused by the nanofin array and then imaged by a reflective microscope 40x objective lens (LMM-40X-P01-160, Thorlabs) in conjunction with an uncooled infrared camera (DM2516, Dali Microelectronics, Inc., Hangzhou, China) that can provide IR monochromatic light in the spectral range from 2-10 μm with a wavelength bandwidth of 60 nm. The IR monochromator is integrated with a compact mirror system to output parallel light. It is also equipped with a linear polarizer (OB0011, Fingqi, Inc., Beijing, China) paired with a quarter-wave plate (OB0005, Fingqi, Inc., Beijing, China) to create circularly polarized output from arbitrarily polarized light since the metalenses are designed to operate for circularly polarized light. The output light passes through metalenses from the backside is focused by the nanofin array and then imaged by a reflective microscope 40x objective lens (LMM-40X-P01-160, Thorlabs) in conjunction with an uncooled infrared camera (DM2516, Dali Microelectronics, Inc., Hangzhou, China), which consists of 160×120 pixels (each pixel size is 25×25 μm²). Note that the objective lens is used here to magnify the focal spots of our metalenses which are much smaller than the pixel size of the IR camera. The magnified focal spots are imaged by the IR camera as shown in Fig. 4(b), (c) and (d). The actual profile of the metalenses focal spots is 40 times smaller than the magnified focal spots. Fig. 4(e)–(g) show that the metalens at 3, 5 and 8 μm has an actual FWHM of 2.16, 3.58 and 5.66 μm, respectively. The measured spot sizes of our metalenses are a little larger than the corresponding theoretical limits by around 20%. We believe that both the proximity of EBL and the crosstalk between adjacent pixels of IR camera may contribute to this deviation. We also measured the light distribution profiles along z-axis (the direction of light propagation) by moving the objective lens and the camera together as shown in Fig. 5(a), where the point at z = 0 is corresponding to the position of focal spot. Probably due to the same reason, the measured z-axis profile is ~15.3 μm, approximately two times of the theoretical value.

To further evaluate the performance of the metalenses, we also measured the dispersion profiles. For this measurement, the microscope objective lens in Fig. 4(a) is removed from the optical measurement setup to reduce optical loss. Due to the fact that all the three fabricated metalenses have similar patterns, only the results for the metalens designed at the wavelength of 5 μm are shown as in Fig. 5(b). The incident light is in the spectral range from 4.3 to 5.7 μm. The black line in Fig. 5(b) shows the focusing efficiency in this spectral range, which follows a similar profile of the simulation results as the black line in Fig. 1(e). The measured focusing efficiency is attained from the ratio of the light power referred from the brightest pixel to the total power incident on the 6×6 mm² metalens. The maximum value at the wavelength of 5 μm is around 33%, which is relatively low due to the large reflection of the planar germanium wafer. Note that the transmittance of the germanium wafer itself in the spectral range from 2-10 μm is measured to be around 45% without anti-reflection coatings (data not shown here). The 33% transmittance indicates an 73% (=33/45) focusing efficiency if the metalenses are coated with antireflection layers. This is consistent with our previous simulated transmittance. The red line illustrates how the focal length changes up to ± 120 μm around 2 mm, as the wavelength shifts from 4.3 to 5.7 μm, showing that our metalenses have a relatively strong dispersion effect. This issue can be solved to realize broad-band metalenses by adopting new structures that were recently demonstrated to suppress the dispersion effect.

It is known that the designed metalenses are sensitive to the polarization of incident light. In spite of this, we explored the possibilities that the metalens designed for mid-infrared range can substitute the traditional lens. As for this, we first used a miniature infrared camera to take a photo of fire produced by a lighter as shown in Fig. 6(a). Then we substituted the camera lens with our fabricated metalens with a circular polarizer placed between the fire and the metalens. The fire from the lighter we used has a temperature of around 300 °C thus the maximum radiation intensity is at around 5 μm according to the Wien’s displacement law:

$$\lambda_{\text{max}} = \frac{b}{T},$$

where $b$ is the Stefan-Boltzmann constant and $T$ is the temperature.

FIG. 6. (a) Photo of lighter fire taken by a commercial infrared imager. (b) Photo of fire from the same lighter taken by the same imager with the camera lens substituted by a metalens designed at 5 μm.
where b is the Wien’s displacement constant equal to 2.898 × 10⁻³ K · m. As a result, we chose the metasurface designed at wavelength of 5 μm and took a second photo of the fire as shown in Fig. 6(b). Clearly, compared to the previous one, the new photo is a little blurrier, in particular in the flame tail where the temperature is lower. This is mainly caused by the dispersion effects of metasurface. As shown in Fig. 5(a), we can see that for the metasurface designed at 5 μm, its focal length shifts rapidly as the wavelength becomes longer than 5 μm. This will result in the fact that the light with different wavelengths is focused at different positions, leading to a blurring image.

III. CONCLUSION

Planar metasurface may allow for the development of miniaturized infrared cameras and chemical sensors. In this work, we designed and fabricated planar metasurface at mid-infrared range by nanostructuring a Ge substrate that is transparent at mid-infrared range. The metasurface can achieve a focusing efficiency of ~ 80% at 3μm, 5μm and 8μm. In comparison with commercial spherical lenses, our metasurface still has a relatively strong dispersion and polarization dependence, which can be solved in the future by adopting new nanoins structures.

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