Thermally Tunable Infrared Metalens Using Phase Change Material

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Abstract

Metamaterials and their two-dimensional forms, metasurfaces, have been studied intensively due to their unique features that usually do not exist in nature. Due to their unusual properties, they have found their way into many different application areas. One of these application areas is metalens application, where the metasurfaces are formed as flat lenses and they bend the wavefront of the outgoing electromagnetic wave. Metalenses are a candidate to replace the spherical lenses because they are much smaller, they are easy to fabricate, and they are a solution to aberration problems. In this paper, a metalens structure with $11\,\mu$m operating wavelength is studied. In addition to working at the long infrared wavelength, the dynamic feature is brought to the metalens with the addition of vanadium dioxide, and power control at the focal point is obtained.

1. Introduction

Metamaterials are artificial engineered structures that can perform unique features because of interaction with electromagnetic waves [1]. These unusual properties such as negative refractive index [2], perfect absorption [3], and targeted camouflage [4] have attracted tremendous interest into the field [5] and many studies have been done since the pioneering work was published [6].

As a two-dimensional planar metamaterial form, metasurfaces are also demonstrated remarkable characteristics in various application areas [7–12]. Control and manipulation of the emergent electromagnetic wavefront are one of the significant implementations of the metasurfaces in the optical device technologies [13]. The flat metasurface lenses called as metalenses are candidates to replace conventional bulky spherical lenses which are one of the obstacles to downsizing the modern optical devices [14].

The traditional lenses control the light propagation path by controlling the phase shift of light continuously using curved surfaces [15]. This spherical shape brings difficulties in the fabrication process and causes aberrations such as spherical and chromatic aberration [16].

On the other hand, metalenses manipulate the incident light by the control of the local refractive indices [14] and with that it can reshape the phase, amplitude, and polarization of the light with an ease [17]. Metalenses compose a number of unit-cells called meta-atoms which are nanofins on top of a period of substrate. This configuration makes the fabrication much easier, and it allows the miniaturizing of the optical devices since the array of the meta-atoms is much smaller than conventional lenses [18].

To mimic the phase profile of the light outgoing from a spherical lens, 2π difference should be achieved using nanofins with different radii while the transmission through each unit is kept as high as possible. As a result of the placement of the meta-atoms at the calculated (x, y), metalens gains a lens property, and it reshapes the wavefront of the electromagnetic wave to focus on the focal point.

Commonly, the visible region is selected as a working wavelength for the studied metalens. Recently, with the usage of germanium (Ge), metalenses that are working at short wavelength infrared region (SWIR) [17] and middle wavelength infrared region (MWIR) [14] are obtained. However, metalenses that are working in long wavelength infrared region need to be studied.

Metalenses which are constructed with metal or dielectric materials are generally passive systems with no dynamic ability [19]. To reach the desired dynamic property, the addition of temperature-sensitive materials is an excellent method. Participation of phase change materials (PCMs) with thermally tunable feature can be an option to bring a tunability to the metalens even after the fabrication [20]. In particular, vanadium dioxide (VO_2) with rapid insulator to metal phase change around the temperature of 68 ℃ [21], can be a promising choice to gain control over the focusing and power of the metalens after production.

In this study, Ge based metalens is built to operate at long infrared wavelength. The focusing ability of the proposed metalens is investigated using electric fields along the propagation direction and the focal point. To obtain dynamic featured metalens, VO_2 from PCMs is added to the structure. The lens behavior of the PCM based metalens is examined for the different temperature around the critical temperature of the VO_2.

2. Design And Simulation

Figure 1(a) is a schematic representation of the germanium (Ge) based metalens including Ge nanofins with the spectral refractive index taken from the CRC Handbook of Chemistry and Physics [22] on top of a silicon dioxide (SiO_2) substrate with optical properties from Handbook of Optical Constants of Solids [23]. The unit cell of the structure named meta-atom is illustrated in Fig. 1(b). Period, height, and width of the meta-atom are set as$p$, h, and w, respectively. The period is constant for all the simulations, and it is chosen as p=450 nm.

The numerical approach is utilized to investigate the optical properties and optimized the parameters of the proposed metalens using the commercial finite-difference time-domain (FDTD) software package (Lumerical FDTD Solutions) [24]. Incident light is a uniform plane wave with a propagation along z direction. Boundary condition for the meta-atom is selected as a perfectly matched layer (PML) for the z direction and periodic for x and y direction.

To construct a metalens to mimic a spherical lens, a 2π phase difference is obtained over the lens using several meta-atoms with different radius. While the radius of each meta-atom is changing between 10 nmto 220 nm, the height and the period are remained constant to achieve effortless fabrication.

Furthermore, to set the optimum height, various sizes of Ge with the same radius change is simulated, as shown in Fig. 1(c). Desired phase difference is achieved when $h=6\ \mu m$. Besides having a 2π phase difference, high transmission is also an important factor to metalens to act as spherical lens. The transmission data is around 0.8 for most of the time, and it is over the $\%\ 60$ for all the radii. The transmission spectrum is demonstrated in Fig. 1(d), when the height is set as $h=6\ \mu m$.

Each meta-atom component is placed at specific $\left(x,y\right)$ on top of a SiO_2 substrate according to the phase equation given below to obtain a spherical lens.

$$\phi \left(x,y\right)=\frac{2\pi }{\lambda }\left(f-\sqrt{{x}^{2}+{y}^{2}+{f}^{2}}\right), \left(1\right)$$

where $\phi \left(x,y\right)$ is a phase profile as a result of changing radius of each nanofin, fis the focal length of the metalens that is set as $15 \mu m$, and λ is the operating wavelength of the design which is chosen as $11 \mu m$.

3. Result And Discussion

Figure 2(a) is an illustration of the behaviour of the proposed metalens under illumination. The metalens is constructed using phase data of the nanofins at different radius given in Fig. 1(d), and placement information of each phase calculated from the Eq. 1. The radius of the metalens is set as $R=11.5 \mu m$. The focusing behaviour of the metalens can be seen in Fig. 2(b). The electric field intensity ${\left|E\right|}^{2}$ is sharply increasing around the focal length which means light is concentrated at that point. The full width half maximum (FWHM) of the electric field peak is around $16.38 \mu m$. The electric field distribution on the x-z plane at $y=0$ and on the x-y plane at the focal point is shown in Fig. 2(c) and 2(d), respectively. To examine the focusing efficiency of the metalens numerical aperture (NA) is calculated as follow.

$$NA =n\times \text{sin}\theta , \left(2\right)$$

where n is the refractive index of surroundings, and θ is the the maximum diffraction angle at the edge of the metalens. Since the medium is air $n=1$ and the focal length and metalens radius is given above, the NA is 0.611.

In addition to the focusing ability of the metalens, as a dynamic feature thermal tuning is incorporated into the metalens using VO_2.

The optical properties of VO_2 is taken from an experimental study [21]. VO_2 is placed with the thickness of $t=100$nm under the nanofins, above the substrate as demonstrated in Fig. 3(a). At the room temperature metalens is acted as when it was without VO_2. However, with the increase of the temperature, VO_2 is transformed into a metal phase and the focusing ability of the metalens is started weakening. The decreasing behaviour of the electric field when the temperature is increasing is shown in Fig. 3(b). The dramatic change of the electric field and the focusing behaviour of the metalens when VO_2 is in the insulator phase or the metal phase is plotted for the z direction in Fig. 3(c), and x and y direction at the focal point in Fig. 3(d) and 3(e).

4. Conclusion

In this study, metalens structure as a candidate to replace the traditional spherical lens is structured at an operating wavelength of 11 \mum. Meta-atoms are formed as Ge nanofins on top of the SiO_2 substrate and the location of each meta-atom is calculated using phase and radius information. The focusing feature of the proposed metalens is investigated using electric field intensity and NA. Moreover, thermally tunability is obtained using VO_2. Metalens is gained dynamic features, and control over the outgoing light power with the addition of the VO_2 even after the fabrication.

Declarations

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Authors' Contributions First author (E.B.) carried out design, simulation, and analysis of the results. Second author (A.G.) helped in simulation and discussion steps of the paper. Last author (E.O.) supervised the study. All the authors contributed in the paper writing.

Data availability All data that support the findings of this study are included within the article (and any supplementary files).

Competing Interests The authors declare that they have no competing interests.

Ethics approval Not applicable

Consent to participate The authors declare that they have concent to participate.

Consent for publication The authors declare that they have concent for publication.

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Figures

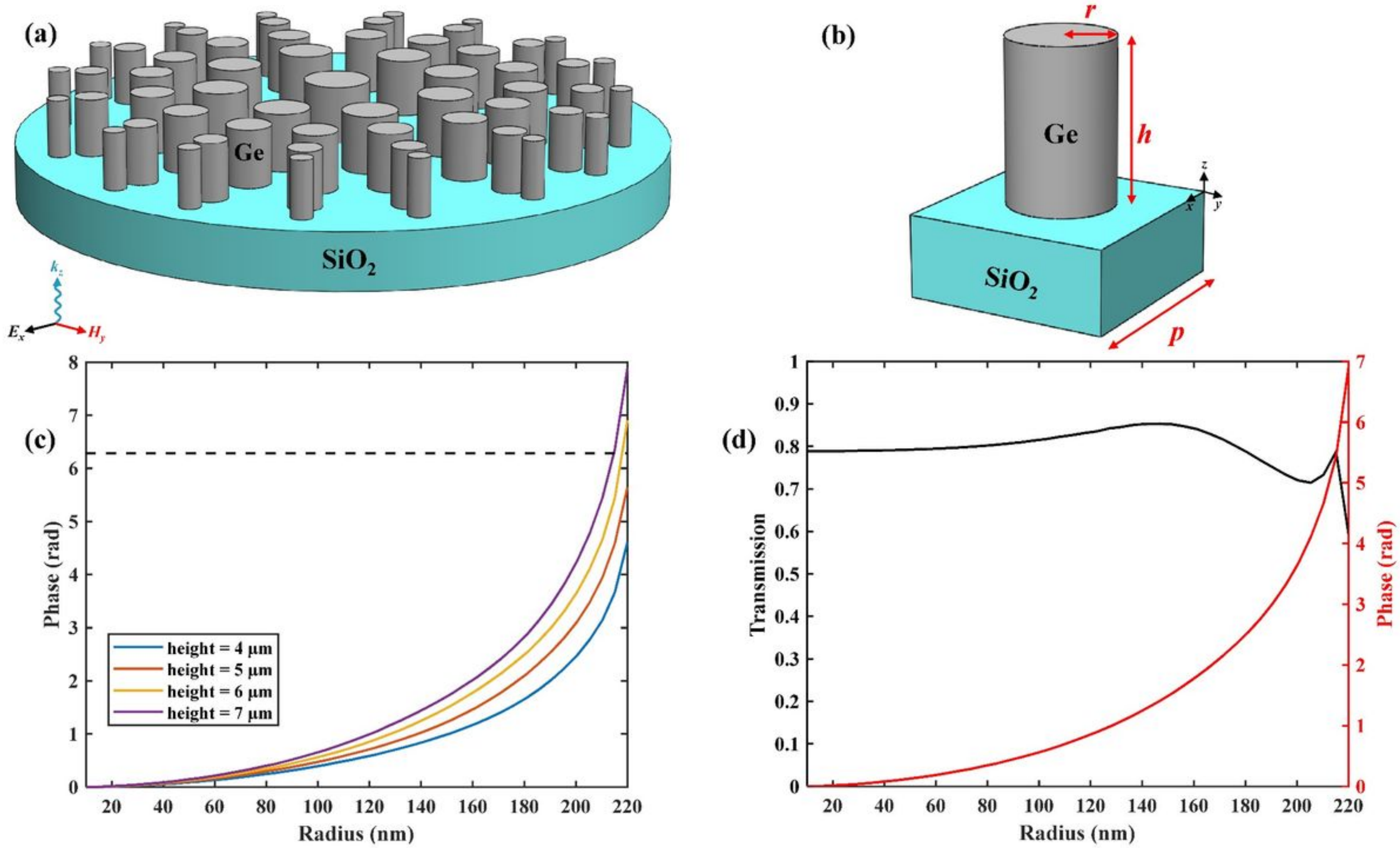

Figure 1

(a) Schematic illustration of the proposed metalens structure with Ge nanofins on top of a SiO2 substrate. (b) A Ge nanofin on top of a SiO_2 substrate with radius *r*, height *h* and period *p*. (c) The phase change of the Ge nanofin at different heights. (d) Transmission and phase change of proposed nanofin structure.

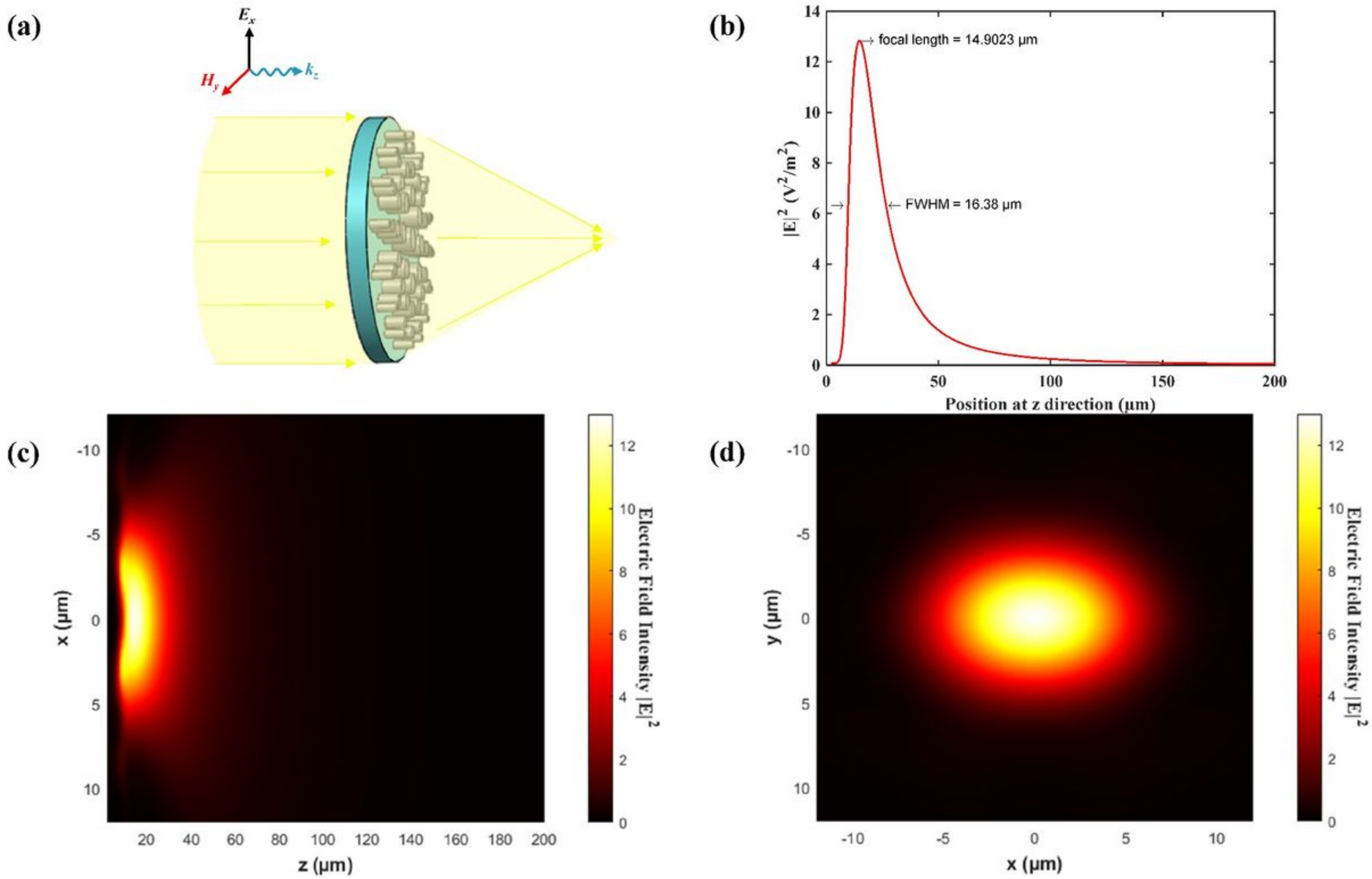

Figure 2

(a) Schematic illustration of the proposed metalens under illumination. (b) Electric field intensity in the z direction. (c) Electric field intensity distribution in the x – z plane. (d) Electric field distribution in the x – y plane at the focal length.

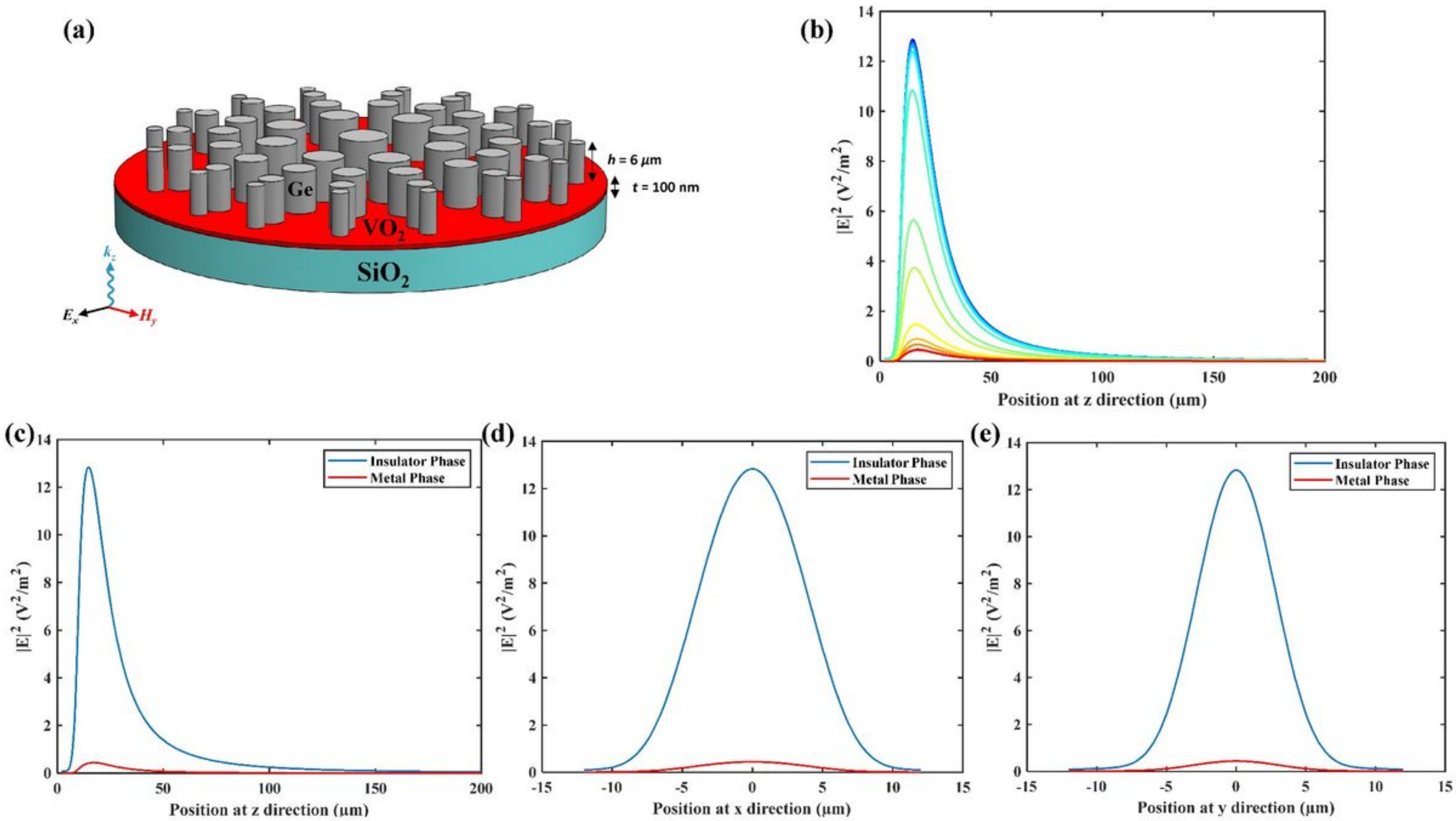

Figure 3

(a) Schematic illustration of the proposed PCM based metalens. (b) Electric field intensity changes in *z* direction with the increase of the temperature from 25°C to 90°C. Electric fields intensity changes in (c) *z* direction, (d) *x* direction, and (e) *y* direction at the insulator phase and the metal phase.