Switchable Wavefront of Mid-Infrared Wave Using GeSbTe Metasurfaces

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Abstract—Benefiting from the unprecedented superiority of phase change material on manipulating electromagnetic wave, germanium antimony telluride-based optical devices attract a lot of attention. Here, based on Pancharatnam-Berry phase, reflective metasurfaces are presented by using phase change material germanium antimony telluride (Ge$_2$Sb$_2$Te$_6$). They can manipulate reflection mode of terahertz wave and realize some functions. In order to verify this, three examples are numerically demonstrated, and they are gradient metasurface, vortex beam generator, and focusing lens. First of all, Ge$_2$Sb$_2$Te$_6$ blocks are used to construct reflective wavefront of gradient metasurface, and then realize switching between anomalous reflection and mirror reflection. Secondly, vortex beam generators are designed with $|l| = 1$ and $|l| = 2$, and mode number of orbital angular momentum is reconstructed through the switching of Ge$_2$Sb$_2$Te$_6$ between crystalline state and amorphous state. Finally, a reflective lens is presented, whose focus appears or disappears under different circular polarizations. By adjusting phase state of Ge$_2$Sb$_2$Te$_6$, dynamic adjustment of focusing intensity is realized. Our design may have potential applications in the fields of terahertz switching and communication.

Index Terms—GeSbTe, metasurface, anomalous reflection, orbital angular momentum, Lens.

I. INTRODUCTION

Electromagnetic metamaterials refer to artificially three-dimensional engineered materials. The combination of specific metal or dielectric structures can realize the manipulation of reflected and transmitted electromagnetic waves. Through some specific arrays, metamaterials realize many novel properties that natural materials do not own, such as negative permeability [1], [2] and negative refractive index [3], [4]. More electromagnetic responses are presented with charming phenomena, such as perfect imaging [5], [6] and invisible cloak [7], [8].

There are some defects in traditional electromagnetic metamaterials, such as large size, high loss, and expensive fabrication cost, and these problems limit the application range of electromagnetic metamaterials to a certain extent. As a two-dimensional planar structure of electromagnetic metamaterial, the appearance of metasurface effectively solves the above problems on the premise of maintaining basic characteristics of metamaterial. Metasurface has ultra-thin characteristic, is easier to process and integrate with devices, and has a wider range of applications. In 2012, Yu et al. demonstrated an optically thin metasurface that generates high-quality circularly polarized light over a broad wavelength range from 5 μm to 12 μm [9]. In 2015, Miao et al. proposed an ultra-thin reflective graphene metasurface with a wide phase modulation range. They used graphene as an adjustable loss to drive the transition from underdamped resonator to overdamped resonator [10]. In 2017, Li et al. presented a 1-bit coding metasurface to generate different high-resolution and low-noise holograms [11]. In 2018, Stav et al. used a dielectric metasurface to generate entanglement between spin and orbital angular momentum (OAM) of photons [12]. In 2020, shirmanshe et al. proposed tunable multifunctional metasurfaces that are capable of dynamic beam steering and reconfigurable light focusing [13]. In 2021, Zhang et al. reported a large-scale and reconfigurable nonvolatile metasurface based on phase change alloy Ge$_2$Sb$_2$Se$_4$Te. They demonstrated quasi-continuously tunable metasurfaces with large spectral tuning range [14].

Recently, active metasurface has aroused extensive research [15], [16]. Phase change materials have contrasting material properties in different states, and they would be an ideal material platform for the realization of active metasurfaces. Among phase change materials used for terahertz devices, the most popular choice is vanadium dioxide, and it is exploited for varied functionalities enabled by insulator-metal phase transition [17], [18]. However, practical use of vanadium dioxide in devices is hampered by its limited multi-level response and complexity of fabrication. In contrast, primary phases of germanium antimony telluride (GeSbTe), amorphous state and crystalline state, are stable for most applications. The state of GeSbTe can be thermally, optically or electrically switched at ultrahigh speed [19]. Furthermore, GeSbTe is extremely scalable and easily integrated [20], [21]. In 2013, Michel et al. demonstrated tuning of resonant frequency of aluminum nanoantenna by changing refractive index of Ge$_2$Sb$_2$Te$_6$ [22]. In 2015, Rios et al. proposed nonvolatile multilevel memory based on Ge$_2$Sb$_2$Te$_5$, and realized up to eight levels of bit storage in a single device [23]. In 2016, Zheng et al. used ultra-thin Ge$_2$Sb$_2$Te$_5$ to realize reversible optical switch of highly confined phonon-polaritons [24]. In 2021, Abdollahramezani et al. presented a reconfigurable hybrid metasurface using Ge$_2$Sb$_2$Te$_5$ for active and nonvolatile tuning of light properties [25].
In this work, switchable metasurfaces are proposed by Ge$_3$Sb$_2$Te$_6$ blocks. Based on Pancharatnam-Berry phase, the designed meta-atoms have 360° phase modulation ability by rotating azimuth angle of the top scatterer. Wavefront of metasurface is reconfigurable and multiple functions are realized. In order to verify this, three examples are presented to demonstrate wavefront reconstruction. Firstly, the designed gradient metasurface is flexibly switched between anomalous reflection and mirror reflection when Ge$_3$Sb$_2$Te$_6$ is switched between crystalline state and amorphous state. Secondly, vortex beam generators are designed. In this case, phase state of Ge$_3$Sb$_2$Te$_6$ rebuilds mode number of OAM. Finally, we show a reflective metalens that switches dynamically between focusing and defocusing.

II. DESIGN AND MODEL

Pancharatnam-Berry phase, also known as geometric phase, was firstly proposed in optical system [26], [27]. Phase response is controlled by change in orientation rather than structural parameters of meta-atoms, which presents different geometric phases under irradiation of different circular polarizations (CPs). Ge$_3$Sb$_2$Te$_6$ metasurfaces are proposed based on Pancharatnam-Berry phase, and metasurfaces are composed of Ge$_3$Sb$_2$Te$_6$ blocks with different directional angles. Fig. 1(a) shows eight meta-atoms numbered 0–7, and rotation angle step of meta-atom is 22.5°. Each meta-atom is composed of gold film and Ge$_3$Sb$_2$Te$_6$ block. Ge$_3$Sb$_2$Te$_6$ has two states-crystalline state and amorphous state. Dielectric permittivity of crystalline state is 42.0 + 1.1i, and that of amorphous state is 12.8 + 0.01i at 80 THz [22]. Drude model $\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + \gamma \omega}$ is used to describe gold. In simulation, $\varepsilon_\infty$ is 12, collision frequency $\gamma$ is $1.05 \times 10^{14}$ rad/s, and plasma frequency $\omega_p$ is $1.37 \times 10^{16}$ rad/s. The details of three-dimensional meta-atom are presented in Fig. 1(b). Finite element method is employed to conduct full-wave simulation.

By adopting Pancharatnam-Berry phase, required phase is achieved. Fig. 2 shows amplitude and phase responses under incidences of left-handed circular polarization (LCP) and right-handed circular polarization (RCP) with different phase states of Ge$_3$Sb$_2$Te$_6$. As shown in Fig. 2(a) and (c), when Ge$_3$Sb$_2$Te$_6$ is in the crystalline state, phase difference between adjacent meta-atoms is always maintained at ~45°. This condition ensures that Pancharatnam-Berry metasurface achieves 360° phase coverage and presents opposite phase response to LCP and RCP. In addition, amplitudes of eight meta-atoms are ~0.9. In contrast, when Ge$_3$Sb$_2$Te$_6$ is in the amorphous state in Fig. 2(b) and (d), reflection phase still meets Pancharatnam-Berry phase, but reflection amplitude is generally reduced to less than 0.2 under incidences of LCP and RCP. Hence, change of reflection amplitude between crystalline state and amorphous state is used to dynamically manipulate reflected wavefront.

III. RESULTS AND DISCUSSIONS

A. Gradient Metasurface

According to the generalized Snell’s law of reflection and refraction, direction of reflection wave is arbitrarily changed by introducing a suitable gradient phase $(d\Phi/dx)$ at interface [28], [29].

$$\sin(\theta_r)n_r - \sin(\theta_i)n_i = \frac{\lambda}{2\pi} \frac{d\Phi}{dx} \tag{1}$$

where $\theta_i$ is incident angle and $\theta_r$ is reflection angle. Gradient phase $(d\Phi/dx)$ is equal to $2\pi/sp$, and $p$ is period of unit cell. The designed meta-atoms form metasurface with a certain phase gradient in Fig. 3(a). Such metasurface will provide an additional wavevector, which change wavefront of reflected beam. Fig. 3(b) shows simulated (circle) and calculated (line) reflection angles at different incident angles. When Ge$_3$Sb$_2$Te$_6$ is in the crystalline state, the phenomena of anomalous reflection are presented under incidences of LCP and RCP corresponding to pink curve and
vortex beams carrying OAM with different modes are used to encode information and increase communication capacity. As shown in Fig. 6, the proposed eight meta-atoms are used to generate vortex beams with different modes. Spiral phase distribution of vortex beam carrying OAM is \( \Phi = e^{i\phi} \), where \( \phi \) is azimuth angle and \( l \) is OAM mode number. A simple method for creating vortex beam is to introduce a spiral-like phase shift, and phase distribution is expressed as

\[
\phi(x, y) = l\phi = l\arctan(y/x)
\]

Phase distribution in Fig. 6(a) consists of eight sectors and each sector corresponds to a specific phase. Discrete phase step is \( \pm 45^\circ \) from a sector to another. Meta-atoms are arranged in Fig. 6(b), and they can realize LCP and RCP vortex beams. Vortex beam with OAM mode of \( l = -1 \) will be generated under LCP incidence. Under RCP incidence, vortex beam with OAM mode of \( l = +1 \) will be generated. Fig. 6(c) shows another metasurface, and it is divided into sixteen sectors. For LCP incidence, vortex beam is generated with OAM mode of \( l = -2 \). For RCP incidence, vortex beam is generated with OAM mode of \( l = +2 \). Fig. 6(d) is the corresponding structure diagram.

In simulation, LCP/RCP wave is assumed to illuminate the designed generators, and results of reflection fields are shown in Fig. 7. For LCP incidence, simulated results in Fig. 7(a) and (c) show that amplitude distribution has a hollow center when \( Ge_Sb_2Te_6 \) is in the crystalline state. This is consistent with the characteristic of vortex beam. Phase distributions show 360° phase rotation in azimuthal direction for \( l = -1 \) and 720° phase rotation for \( l = -2 \). Reflection efficiencies of the proposed vortex beam generators are 83.6% for \( l = -1 \) and 72.0% for \( l = -2 \). When \( Ge_Sb_2Te_6 \) is switched to amorphous state, vortex beam generator achieves OAM mode conversion from \( l = -1 \) or \( l = -2 \) to \( l = 0 \). Plane wave and uniform phase are observed. For RCP incidence, results in Fig. 7(b) and (d) show that amplitude distribution has a hollow center when \( Ge_Sb_2Te_6 \) is crystalline. Phase distribution presents a spiral distribution, and changes...
of 12 μm and a focal length of \( f_0 = 10 \mu m \). Phase profile is discretized in a step of 45° in the x-y plane and represented with proper meta-atom in Fig. 8(b). Fig. 8(c) and (d) show intensity distributions when LCP wave is normally incident at 80 THz. Results show that metalens realizes defocus function regardless of phase state of Ge\(_3\)Sb\(_2\)Te\(_6\). On the contrary, when Ge\(_3\)Sb\(_2\)Te\(_6\) is in the crystalline state for RCP incidence, incident wave converges to focus at \( z = 9.4 \mu m \). Full width at half maximum of focal point is 2.20 μm in Fig. 8(e). Focusing efficiency of metalens is 62.8%. When Ge\(_3\)Sb\(_2\)Te\(_6\) switches to amorphous state, Fig. 8(f) illustrates that incident wave converges to focus at \( z = 9.4 \mu m \). Full width at half maximum of focal point is 2.32 μm, and focusing efficiency is 1.7%. Therefore, the designed metalens realizes defocusing of LCP and focusing of RCP, and focusing intensity of RCP is dynamically adjusted by phase state of Ge\(_3\)Sb\(_2\)Te\(_6\).

IV. CONCLUSION

In conclusion, switchable metasurfaces are presented based on Ge\(_3\)Sb\(_2\)Te\(_6\) blocks to control electromagnetic wave. Based on Pancharatnam-Berry phase, the proposed meta-atoms have phase modulation ability of 360° and show opposite geometric phase for LCP and RCP incidences. When Ge\(_3\)Sb\(_2\)Te\(_6\) is in the crystalline state, the overall reflection amplitude is ~0.9, while Ge\(_3\)Sb\(_2\)Te\(_6\) is switched to amorphous state, reflection amplitude decreases to less than 0.2. Therefore, the change of reflection amplitude is used to dynamically adjust the reflected wavefront. Gradient metasurface, vortex beam generator, and metalens are designed. It is found that the proposed gradient metasurface can switch between anomalous reflection and mirror reflection for different phase states of Ge\(_3\)Sb\(_2\)Te\(_6\). In addition, OAM modes of vortex beam are \( l = \pm 1, l = \pm 2 \), and \( l = 0 \), and \( l \) is reconstructed by different states of Ge\(_3\)Sb\(_2\)Te\(_6\). Finally, the designed metalens realizes focusing of RCP and defocusing of LCP, and focusing intensity of RCP is changed by switching between crystalline state and amorphous state of Ge\(_3\)Sb\(_2\)Te\(_6\). Our work may provide a new perspective for the design of active metasurfaces.

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