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All-graphene geometric terahertz metasurfaces for generating multi-dimensional focused vortex beams

Hui Li [a], Chenglong Zheng [a], Hang Xu [a], Jie Li [a], Chunyu Song [a], Fan Yang [a], Jitao Li [a], Wei Shi [a], Yating Zhang [a], Jianquan Yao [a b]

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Abstract

Simultaneously assembling the functions of lenses and phase vortices into geometric metasurfaces on an ultra-compact platform can potentially be used for light trapping and edge imaging, helping to enhance their applications in polarized optical systems. Here, we propose and theoretically investigate an all-graphene geometric metasurface operating in the terahertz (THz) band for generating multidimensional vortices. Focused scalar vortex beams with polarization-independent properties can be generated by introducing the superposition of two helical phases with the same topological charge within orthogonal circularly polarized (CP) channels. Focus shift can be further tolerated by tailoring the conventional helical phase distribution. Embedding polarization modulation into the proposed design enables the generation of multiple focused vortices with inhomogeneous polarization properties in the longitudinal direction. The typical conjugate phase is capable of generating aggregated vortices with vectorial characteristics by switching the incident polarization mode, and can be extended to arbitrary orders. Using the way in which the graphene Fermi energy was changed in the simulation provides strong evidence for dynamically tuning the focusing efficiency of the generated beam. Benefiting from the proposed method that manipulates the orthogonal CP components separately, the design scheme has greater degree of freedom and can find potential applications in *meta*-optics, high-tolerance edge imaging, and high-capacity optical communications.

Introduction

Vortex beam, also known as phase vortex beam, that is, the phase or wavefront of the light exhibits a spiral shape, and its complex amplitude expression in the cylindrical coordinate system (r, ψ, z) contains the spiral phase term $\exp(il\psi)$, with ψ represent the azimuthal angle in the transverse plane and l is the topological charge [1], [2], [3]. The electric field distribution of the vortex beam shows a typical doughnut-shaped profile due to the presence of a phase singularity in the center of the beam [4]. Furthermore, the amount of distortion of vortex and the direction of the helical phase distribution depends on the magnitude and direction of an arbitrary integer l [5], [6]. Because of the spiral wavefront phase distribution, vortex beams exhibit unique properties not found in ordinary Gaussian beams, making them potentially valuable in many fields, including optical processing [7], astronomical detection [8], and quantum information processing [9], and so on. In fact, when a focused vortex with a predefined focal plane acts on a particle, the orbital angular momentum carried by the beam can be transferred to the particle, allowing a high degree of flexibility to manipulate the rotation and translation of the particle, especially for polarization-dependent particles [10].

Terahertz radiation, an electromagnetic wave with a wavelength between 3 μm and 3 mm, has excellent coherence and broadband properties, can find great applications in high-capacity communications. The emergence of metasurfaces, on the other hand, has accelerated the miniaturization and integration of THz-enabled devices [11], [12], [13], [14]. Geometric metasurfaces are novel quasi-2D structures consisting of pre-designed anisotropic *meta*-atoms with the same geometric parameters but different orientation angles, which can provide accurate modulation of the amplitude, phase, and polarization modes of incident waves on an ultrathin platform [15], [16]. Metasurface-based wavefront manipulation depends on the spatial orientation angle of the *meta*-atoms with respect to the x-axis, also known as the Pancharatnam-Berry (PB) phase, rather than the phase (propagation phase) accumulation along the optical path [17], [18], [19]. Benefiting from the frequency independence and high degree of freedom of PB phase profiles, geometric metasurfaces are optimal candidates for integrated optical systems [20]. Including easy fabrication, ultrathin components, and multifunctional integration properties, metasurfaces with geometric phase distributions can be used to generate various types of vortex beams with arbitrary topological charges. Examples include scalar vortex beams [21], [22], vector vortex beams [23], [24], [25], perfect vortex beams [26], [27], [28], and polarization multiplexing of multiple vortex beams [29], [30], [31]. Unfortunately, most of the recently reported geometric metasurfaces are merely designed for CP incidence and do not possess dynamically tunable properties [32].

THz functional devices with actively tunable characteristics are a hot research topic in recent years, and the two most widely used materials are graphene and vanadium dioxide (VO_2) [33], [34], [35], [36]. Graphene is a single-layered two-dimensional honeycomb material made of tightly packed carbon atoms connected by sp^2 hybridization, which has excellent optical, electrical, and mechanical properties and holds important promise for applications in micro and nano sensing [37], [38], biomedicine [39], [40], [41], and vortex generation [42], [43], [44], [45]. Moreover, the surface conductivity of graphene is determined by its Fermi energy, and the surface plasmon excitonic effect of monolayer graphene in the THz band can be dynamically tuned by applying an external bias voltage [46], [47], [48], [49], [50]. On the other hand, to the best of our knowledge, the previously reported graphene-based *meta*-platforms can produce vortex beams with controlled efficiency, but they are unable to carry inhomogeneous polarization states in the transverse plane [42], [43], [44], [45], which is hardly adaptable to the future development of quantum communication technology.

In this paper, we propose an all-graphene metasurface based solely on the geometric phase profiles, which is designed to generate multi-functional vortex beams in transmission mode by switching the incident polarization. The generation of scalar vortex beams with polarization-insensitive characteristics is obtained by independent encoding of the orthogonal CP channels. By introducing an encoding scheme with a long focal depth focusing phase profile, the polarization rotatable function can be further integrated into a monolayer geometric *meta*-platform, resulting in a focused vortex beam with an extended focal depth. Also, by carefully assembling the phase factors within the CP channels with different spin states, the proposed design enables multidimensional polarization multiplexing based on polarization rotatability. Taking full advantage of the conjugate property of the geometric phase, the design can produce a high-order vector vortex beam with inhomogeneous polarization states under linearly polarized illumination. In addition, the manipulation of the Fermi energy of graphene allows flexible tailoring of the vortex beam focusing efficiency. Benefiting from the geometric phase flexibility, the designed all-graphene geometric metasurfaces for polarization multiplexing and vector vortex focusing can find potential applications in *meta*-optical systems.

Section snippets

Design and simulation methods

The schematic diagram of the polarization *meta*-platform operating in the THz band used to generate the focusing vortex beam is shown in Fig. 1(a). Monolayer patterned graphene-based C-shaped split ring resonators (CSRRs) are embedded on the upper and lower sides of the dielectric layer for increasing the transmittance of the periodically distributed *meta*-atoms, as displayed in Fig. S1 (Supplementary Information Note 1). A spacer of Ion-gel with a thickness of 1 μm was introduced on the surface…

Results and discussions

Firstly, as shown in Fig. 2(a), the proposed metasurface can be used to focus incident waves with arbitrary polarization states into a scalar vortex beam, carrying the same topological charge. Before performing the encoding algorithm, the incident mode can be divided into two orthogonal CP components, i.e., the LCP and RCP modes. It is well known that the geometric phase profile has a conjugate locking effect within a pair of orthogonal CP channels. In order to simultaneously focus the LCP and…

Conclusions

In conclusion, by continuously rotating the orientation angle of the all-graphene *meta*-atoms, thereby introducing a geometric phase profile, a method that operates in the THz band and can independently manipulate a pair of orthogonal CP components is demonstrated. The application of pure geometric phase greatly simplifies the complexity of structure design, so that there is no need to establish an additional parameter library by scanning the structural parameters of a large number of *meta*…

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Data Availability.

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

CRediT authorship contribution statement

Hui Li: Conceptualization, Methodology. **Chenglong Zheng:** Methodology, Software. **Hang Xu:** Data curation. **Jie Li:** Data curation. **Chunyu Song:** Investigation. **Fan Yang:** Investigation. **Jitao Li:** Investigation. **Wei Shi:** . **Yating Zhang:** Supervision. **Jianquan Yao:** Supervision.…

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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