Dual-wavelength Terahertz Metalens Based on Geometric Phase Metasurface

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Abstract We proposed a novel dual-wavelength meta-atom, which could be used to independently modulate the geometric phase of the circularly polarized incident wave at two terahertz frequencies. A prototype dual-wavelength metalens has been designed and verified at the terahertz regime.

OCIS codes: (160.3918) Metamaterials; (110.6795) Terahertz imaging; (310.6628) Subwavelength structures

1. Introduction

Metasurfaces have attracted enormous attentions since their emergence thanks to the abilities to manipulate the polarization, phase and/or amplitude of the incident electromagnetic waves with ultra-thin subwavelength meta-atoms [1,2]. So far, it has been demonstrated that many traditional bulky devices can be replaced by metasurface-based meta-devices, such as waveplates and meta-lenses. However, most of the reported metasurfaces are designed to work only at one single frequency/wavelength due to the dispersive nature. The wavelength-dependent behavior of the metasurface greatly hinders the design freedom at different wavelengths, thus, a number of studies have been conducted to realize multi-wavelength meta-devices [3-7]. In this work, a novel single-layer meta-atom (unit cell) is proposed to work at two arbitrary terahertz (THz) frequencies. The full 2π phase coverage known as geometric phase (PB phase) can be easily obtained by rotating the resonators. Based on this meta-atom, several meta-devices have been designed and fabricated. As a demonstration example, a dual-wavelength cylindrical metalens is presented.

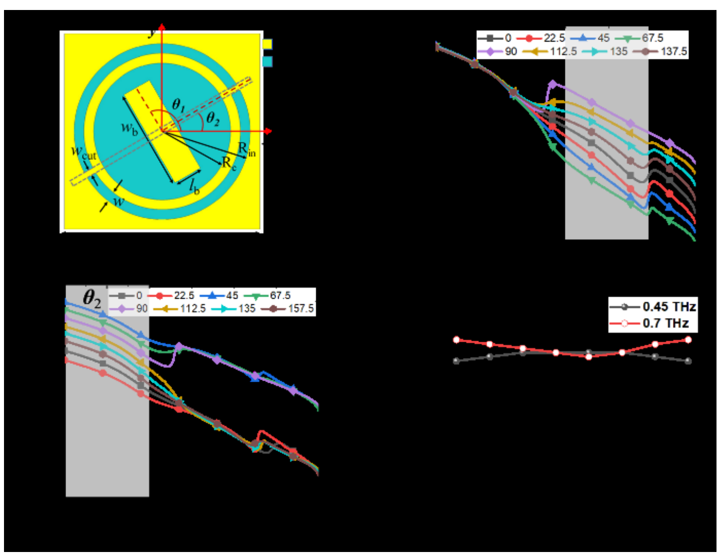

Figure 1 (a) Schematic of the proposed dual-wavelength THz meta-atom; (b) The phase shift by rotating θ_1 with a step interval of 22.5° and a fixed θ_2=0; (c) The phase shift by rotating θ_2 with a step interval of 22.5° and a fixed θ_1=0; (d) The transmission coefficients at 0.7 THz for 8 cells in (b) and at 0.45 THz for 8 cells in (c).

2. Metasurface Design and Results

Schematic of the proposed dual-wavelength meta-atom is illustrated in Fig. 1(a), which is composed of a metallic bar resonator and a double C-slot resonator separated by a circular hole printed on a silicon substrate. At two arbitrary operating frequencies, phase shifts from 0 to 2π can be obtained by simply rotating the angle θ_1/θ_2 for a circularly polarized incident wave, which is known as geometric phase. Fig. 1(b) plots the phase shifts of 8 cells by rotating θ_1 with a step interval of 22.5° and a fixed θ_2=0. It can be observed that these 8 cells show almost constant phase shifts in the shadow area around 0.7 THz while the phase shift remains unchanged at 0.45 THz. Similar phenomenon can be obtained by rotating θ_2 with a fixed θ_1, which is shown in Fig. 1(c). The transmission coefficients at 0.7 THz for 8 cells in Fig. 1(b) and at 0.45 THz for 8 cells in Fig. 1(c) are plotted in Fig. 1(d). It can be seen that the transmission coefficients for these two cases keep almost constant with slight fluctuations. Therefore, the proposed meta-atoms can be used to modulate the phase of the circularly polarized incident wave at two pre-assigned terahertz frequencies independently, which provides a facile way to realize dual-wavelength phase modulation.

To demonstrate the performance of the proposed dual-wavelength meta-atoms, a dual-wavelength cylindrical metalens is designed. It consists of 101 cells and the phase profiles of each cell can be calculated by equation (1):

$$\varphi(x, \lambda_i) = \frac{2\pi}{\lambda_i}\left(\sqrt{x^2 + F^2} - F\right) \quad (1)$$

where x is the distance from each cell to the origin point, F is the focal length and λ_i is the operation wavelength. It is noticed that the required phase shift profile is dependent on the operation wavelength. The dual-wavelength cylindrical metalens is designed to focus the incident light at F=5 mm at both 0.45 and 0.7 THz. Fig. 2(a) and Fig. 2(b) demonstrate the required phase compensations and digitized phase shifts at 0.45 THz and 0.7 THz, respectively. Fig. 2(c) and Fig. 2(d) plot the simulated left-handed polarized electric field on the XZ-plane at 0.45 THz and 0.7 THz by commercial software CST Microwave Studio with a right-handed circularly polarization incidence, respectively. In addition, the normalized intensity on the focal plane at z=5 mm for 0.45 THz (0.7 THz) is plotted on the top of Fig. 2(c) (Fig. 2(d)), which indicates a nearly diffraction limited focusing performance of the proposed dual-wavelength THz metalens. Furthermore, the photo of a fabricated sample including several designed meta-devices is shown in Fig. 2(e), which is under characterization. The detailed measurement results will be reported later.

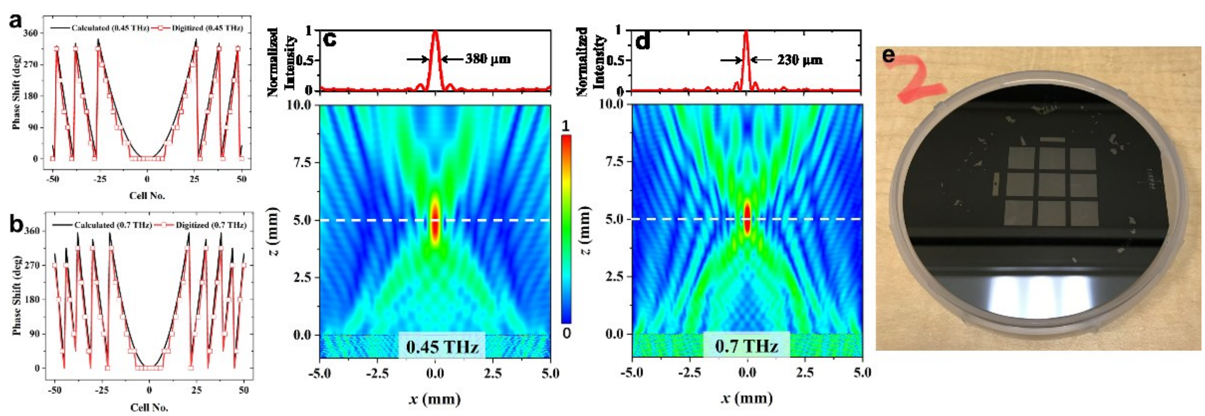

Figure 2 The required and digitized phase profiles for the dual-wavelength metalens at (a) 0.45 THz and (b) 0.7 THz; the simulated left-handed circularly polarized electric field under a right-handed circularly polarization incidence at (c) 0.45 THz and (d) 0.7 THz; (e) the photo of a fabricated sample based on the proposed meta-atoms.

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References

[1]. Yu, Nanfang, et al. "Light propagation with phase discontinuities: generalized laws of reflection and refraction." Science 334.6054 (2011): 333-337.
[2]. Lin, Dianmin, et al. "Dielectric gradient metasurface optical elements." science 345.6194 (2014): 298-302.
[3]. Aieta, Francesco, et al. "Multiwavelength achromatic metasurfaces by dispersive phase compensation." Science 347.6228 (2015): 1342-1345.
[4]. Ding, Jun, et al. "Multiwavelength Metasurfaces Based on Single-Layer Dual-Wavelength Meta-Atoms: Toward Complete Phase and Amplitude Modulations at Two Wavelengths." Advanced Optical Materials 5 (2017).
[5]. Chen, Weiting, et al, "A broadband achromatic metalens for focusing and imaging in the visible." Nature Nanotechnology,13.3 (2018): 220–226.
[6]. Wang, Shuming, et al. "A broadband achromatic metalens in the visible." Nature Nanotechnology,13.3 (2018): 227–232.
[7]. Chen, Weiting, et al, "Broadband Achromatic Metasurface-Refractive Optics." Nano Letters, (2018).