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## Multipolar-interference-assisted terahertz waveplates via all-dielectric metamaterials

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Polarization control via metamaterials boosts the design of polarimetric devices in the realm of terahertz technology for sensitive detection, bio-imaging, and wireless communication. Here, we propose all-dielectric metamaterials composed of silicon brick arrays that operate as terahertz quarter- and half-waveplates with close to unity transmission. Spherical multipole decomposition calculation indicates that the silicon brick can support multiple Mie-type resonances, such as electric dipole, electric quadrupole, magnetic dipole, and magnetic quadrupole modes. By tailoring the multipolar interference among these resonances, near unity transmission can be obtained with over  $\pi$  phase delay. We experimentally realize dielectric terahertz metamaterials that function as a quarter-wave plate at 0.79 THz and a half-wave plate at 0.91 THz with insertion losses of 0.54 and 1.25 dB, respectively. Such anisotropic dielectric metamaterials promise an exotic approach to engineer the interference among multipolar resonances and reveal the feasibility to realize functional, efficient, and compact terahertz meta-devices. © 2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http:// creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5063603

The last decade has witnessed the rapid development of electromagnetic (EM) wave manipulation in the area of metamaterials.<sup>1–3</sup> In particular, polarization control via metamaterials in the terahertz regime attracts much research attention because valuable information conveyed by the polarization states is of great importance for terahertz applications, such as bio-imaging, nondestructive testing, sensing, and communication.<sup>4–7</sup> For instance, terahertz quarter waveplates, which convert linearly polarized light into circularly polarized light, are crucial for terahertz bio-imaging and sensing because many bio-molecules exhibit unique responses with circularly polarized terahertz light.<sup>8</sup> Another example is terahertz half-waveplates for applications in astronomy,<sup>9</sup> in which polarization angles need to be modulated.

Conventional approaches for terahertz polarization conversion are based on birefringent materials or total internal reflection effects, which present many constraints, such as limited available materials, bulky, single-function operation, narrow band, and high loss. Metamaterials, on the other hand, offer an exotic way to control terahertz polarization at will with high performance.<sup>10–12</sup> Various metallic metamaterial designs have been realized for terahertz polarization control, such as anisotropic metasurfaces,<sup>11,13,14</sup> chiral structures,<sup>15</sup> and multilayer gratings.<sup>3,16,17</sup> However, the anisotropic metasurface designs suffer from low operating efficiencies (around 60%) and small phase delays (below  $\pi$ ).<sup>11,13,17</sup> These limitations could be mitigated by employing

chiral and multilayer designs,<sup>3,15–17</sup> but they would bring other problems, such as extra loss and a complex fabrication process. Active medium has been further inserted into these designs for multi-function operation,<sup>15,18</sup> which inevitably bring high losses and a complex fabrication process. With the rapid development of terahertz technology, it is highly desirable to design exotic metamaterials for highly efficient and functional terahertz polarization control devices.

In this work, we theoretically propose and experimentally demonstrate highly efficient terahertz waveplates via all-dielectric metamaterials. Compared with their metallic counterparts, dielectric metamaterials are free of intrinsic Ohmic losses, which naturally enable EM wave controls with high efficiencies.<sup>19-25</sup> Another advantage of dielectric metamaterials is the capability of simultaneous excitation of electric and magnetic resonances. The interference of electric and magnetic resonances opens up the possibility to fully control EM waves with near perfect conversion efficiency and  $2\pi$  phase change, <sup>26,27</sup> which is challenging to be achieved via metallic metamaterials where electric resonances dominate. This is similar to Kerker's condition, which illustrates the directional scattering by interference between electric and magnetic resonances. However, high order resonance modes are not initially considered because the primary dipolar modes and other high order modes would not overlap in those rudimental structures.<sup>21,26</sup> A generalized Kerker's condition has then been developed for more complex antenna geometries, in which high order modes are overlapped with the primary dipolar modes and play significant roles in the ultimate scattering directivities.<sup>28,29</sup>



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Here, we adopt this principle and design an anisotropic silicon brick with the dimension along the wave propagation direction close to the wavelength scale as shown in Fig. 1(a), which enables the simultaneous excitation of both dipole and quadrupole resonances. By modifying the geometry of the silicon brick, dipole and quadrupole modes could overlap. In principle, as shown in Fig. 1(a), the backward scattering would be suppressed when the electric dipole and magnetic quadrupole modes destructively interfere with magnetic dipole and electric quadrupole modes. With a proper control of the multipolar interference in this anisotropic design, near perfect transmission and large phase change along different axes are achievable. As shown in Fig. 1(b), the proposed dielectric metamaterials could function as a quarter-wave plate and convert a linearly polarized light into a circularly polarized light. Furthermore, they can also operate as a halfwave plate and rotate the polarization of the incidence by 90°. Compared with terahertz waveplates made of birefringent materials with beyond millimeter thickness, the functionality of this meta-device is achieved with a device thickness of wavelength scale, which is superior for compact terahertz system integration. Moreover, the multipolar interference effect enables a flexible means to control terahertz wave with high transmission efficiency and large phase variation.

To validate the multipolar interference in the proposed design, the scattering cross sections contributed by various modes of the silicon brick in the array are first calculated with the spherical multipole decomposition method. Silicon is regarded as a lossless material with a permittivity of  $\varepsilon_{r1} = 11.7$  in the terahertz region. The dimensions of the silicon brick, as shown in Fig. 1(a), are w = 35, l = 105, and  $h = 190 \,\mu$ m, respectively. The silicon brick is arranged in a square lattice with a periodicity of 150  $\mu$ m. The numerical simulation is performed using the finite-difference-time-domain method. A broadband terahertz wave is illuminated



FIG. 1. (a) Schematic of proposed silicon brick with the sketch of the scattering patterns for electric dipole (ED), magnetic dipole (MD), electric quadrupole (EQ), and magnetic quadrupole (MQ) modes under a linear polarized incidence. (b) Schematic of metamaterials composed of silicon brick arrays. Under a normal incidence with the polarization at  $\theta = 45^{\circ}$  to *x*-axis, the proposed anisotropic design can simultaneously operate as a quarter-wave plate and a half-wave plate at  $f_1$  and  $f_2$ . The bottom inset is the simulated ellipticity of the transmitted terahertz waves, indicating a circular polarized light at  $f_1$  and a rotated linearly polarized light at  $f_2$ .

on the structure in the z direction. In the simulation, we gradually change w and l from 30 to 120  $\mu$ m, while keeping the height of the silicon brick  $h = 190 \,\mu$ m and period  $p = 150 \,\mu$ m. In order to optimize the performance of the waveplates, we examine the transmission coefficients and phase delay simultaneously. The dual-functional operation is obtained when the transmission coefficients along x- and yaxes reach unity while the phase delays are above  $\pi$ . The corresponding internal current density J in the silicon brick in the array can be written as  $J(r) = -i\omega[\bar{\epsilon}(r) - \epsilon_0]\bar{E}_{inter}(r)$ , where  $\omega$  is the angular frequency,  $\epsilon_0$  is the vacuum permittivity, and  $\bar{E}_{inter}(r)$  is the internal electric field distribution inside the silicon brick extracted from full wave numerical simulation. The electric current density is decomposed into *l*th-order current multipole moments as

$$\boldsymbol{M}^{(l)} = \frac{\mathrm{i}}{(l-1)!\omega} \int \boldsymbol{J}(\boldsymbol{r}) \underbrace{\boldsymbol{rr...r}}_{l-1 \text{ terms}} \mathrm{d}^{3}\boldsymbol{r}, \tag{1}$$

where  $M^{(l)}$  is a tensor of rank *l*. The first and second order current multipole moments correspond to dipole and quadrupole moments. The resultant scattering cross section  $C_s$  of the silicon brick can then be calculated using the following equation:

$$C_s = \frac{\pi}{k^2} \sum_{l=1}^{\infty} (2l+1) \left[ |a_E(l)|^2 + |a_M(l)|^2 \right], \tag{2}$$

where k is the wave number, and the multipole coefficients  $a_E(l)$  and  $a_M(l)$  can be obtained straightforwardly based on the elements of  $M^{(l)}$ .<sup>30,31</sup>

As shown in Fig. 2(a), under x-polarized incidence, the silicon brick simultaneously supports electric dipole, magnetic dipole, electric quadrupole, and magnetic quadrupole modes at around 1.2 THz. This indicates that the silicon brick can not only excite high order quadrupole modes but also make the modes overlap with each other. Similarly, Fig. 2(b) presents the decomposed scattering cross sections under ypolarized incidence. It is observed that the dipole and quadrupole modes are overlapped at around 0.75 and 0.95 THz. The electric dipole, magnetic dipole, and electric quadrupole modes are overlapped at around 0.75 THz, while magnetic dipole, electric quadrupole, and magnetic quadrupole modes are overlapped at around 0.95 THz. The difference of the resonance frequency of multipole modes shows that silicon brick is capable of supporting different combinations of multipole modes, which lead to different multipolar interference effects. As shown in Fig. 1(a), the interference of different resonance modes would change the scattering efficiency and modify the phase dispersion. The multipolar interference can be further tailored for desired functions by modifying the geometry of the silicon brick. Compared with dielectric metamaterials that associate with only electric and magnetic dipoles, the proposed design provides multiple combinations of resonance modes and enables versatile means to manipulate EM waves. More importantly, the superposition of multiple modes releases the rigid Kerker's condition for perfect forward scattering where the electric dipole and magnetic dipole must possess the same resonance frequency, the same amplitude, and the same quality factor.<sup>26</sup> The total scattered





FIG. 2. Scattering cross sections of the silicon brick, depending on different multipole modes under x-(a) and y-(b) polarized terahertz incidences.

field of the silicon brick is the balance of multipole resonance modes, which resembles to the generalized Kerker's condition.<sup>19,28</sup>

Based on the multipolar resonances and their interference effects, silicon brick arrays are designed to control terahertz waves. The simulated transmission and phase delay are shown in Figs. 3(a) and 3(b). It is observed that under x- and y-polarized incidences, both  $|\bar{t}_{y}|$  and  $|\bar{t}_{y}|$  maintain high transmission below 0.92 THz. In particular, at  $f_1$ =0.78 THz, the transmission amplitudes of  $|\bar{t}_x|$  and  $|\bar{t}_y|$  are 0.9 and 0.96, respectively, and the phase delay is  $\varphi_{diff} = 90^\circ$ , as shown in Fig. 3(b). This indicates that such metamaterials can operate as a quarter waveplate at 0.78 THz when the incident light is polarized at  $\theta = 45^{\circ}$  to x-axis. Similarly, the transmission amplitudes of  $|\bar{t}_x|$  and  $|\bar{t}_y|$  are 0.94 and 0.97, respectively, with a phase delay of 180° at 0.90 THz, meaning that this design can function as a half-wave plate. The close to unity transmission is due to the multipolar interference effects, which suppress the backward scattering. The large phase delay can be illustrated by examining the phase shift of the transmitted terahertz wave. When a resonator goes through its resonance, a phase shift would occur. In our proposed design, the dipole and quadrupoles modes are superimposed at low frequencies around 0.75 and 0.95 THz under y-polarized incidence, while under x-polarized incidence these four resonances are overlapped at high frequencies around 1.3 THz, as shown in Fig. 2. Therefore, at lower frequencies (below 1.3THz), y-polarized incidence shows a large phase shift compared with the case of x-polarized incidence (see Fig. S4 in the supplementary material). As a result, an increasing phase delay between y- and x-axes can be

FIG. 3. (a) Simulated transmission and (b) phase delay of the silicon brick arrays under *x*- and *y*-polarized incidences.

observed in this frequency region. In our case,  $90^{\circ}$  and  $180^{\circ}$  phase delays occur at 0.79 and 0.91 THz, respectively, which is challenging to be achieved in other single layer metamaterials. The excitation of dipole and quadrupole modes can be further confirmed with the simulated electric and magnetic field distributions (see Figs. S1 and S2 in the supplementary material).

In order to experimentally demonstrate highly efficient functional terahertz waveplates, the silicon brick arrays were fabricated and measured in the terahertz time-domain spectroscope (THz-TDS). The details of the fabrication process and measurement can be found in the supplementary material. The scanning electron microscopy (SEM) images of the fabricated metamaterials are shown in Figs. 4(a) (tilted-view) and 4(b) (top-view). During the measurement, the electric fields of the transmitted terahertz pulses along x- and y-axes were obtained and denoted as  $\bar{E}_x$  and  $\bar{E}_y$ . A bar substrate was tested as a reference with the transmitted electric fields of  $\bar{E}_{x(ref)}$  and  $\bar{E}_{y(ref)}$ . After fast Fourier transformation to convert the time domain signal into the frequency domain, transmission amplitudes of the dielectric metamaterials were obtained as  $|\bar{t}_x| = \bar{E}_x/\bar{E}_{x(ref)}$ and  $|\bar{t}_y| = \bar{E}_y/\bar{E}_{y(ref)}$ , as shown in Fig. 4(c). The phase delay was calculated as  $\varphi_{diff} = \varphi_v - \varphi_x = \arg(\bar{t}_v) - \arg(\bar{t}_x)$ , which is shown in Fig. 4(d). As can be seen, at  $f_1 = 0.79$  THz, the transmission amplitudes of  $|\bar{t}_x|$  and  $|\bar{t}_y|$  are 0.9 and 0.97, respectively, while their phase delay is 90°. At  $f_2 = 0.91$  THz, the transmission amplitudes of  $|\bar{t}_x|$  and  $|\bar{t}_y|$  are 0.87 and 0.86, respectively, with a phase delay of 180°. Therefore, such metamaterials operate as a quarter-wave plate and a half-wave plate with high efficiency at  $f_1$  and  $f_2$ , respectively, which is in agreement with the simulation results. A small discrepancy of



FIG. 4. SEM images of the fabricated dielectric metamaterials in the tilted view (a) and top view (b) with a zoomed-in image. The scale bars are 200  $\mu$ m. THz-TDS measured (c) transmission amplitude and (d) phase delay of fabricated silicon brick arrays.

the transmitted amplitude can be observed between experimental and simulation results, which may be due to the size fluctuation during the fabrication. It is worth noting that the influence of the substrate is eliminated by using the transmission of it as a reference. In practice, the insertion losses and Fabry-Perot interference in the substrate normally lower the transmission of the device, which is discussed in the supplementary material (see Fig. S3). Nevertheless, the insertion loss can be minimized by using low-loss materials with a lower refractive index and a smaller thickness, such as ultrathin quartz<sup>32</sup> and PDMS.<sup>33</sup> In this work, we readily use the above treatment to validate that our proposed dielectric metamaterials with multipolar resonances are capable of designing terahertz waveplates with high efficiencies.

The performance of polarization conversion in the dielectric metamaterials is investigated by calculating Stokes parameters based on the measured and simulated results.<sup>17</sup> Since this meta-device is operating under a normal incidence polarized at  $\theta = 45^{\circ}$  to *x*-axis, the electric field of the terahertz wave can be expressed as:  $\bar{E} = \bar{E}_x + \bar{E}_y = \bar{t}_x \cos \theta + \bar{t}_y \sin \theta$ . Thus, Stokes parameters  $S_0$ ,  $S_1$ ,  $S_2$ , and  $S_3$  of the output terahertz wave can be calculated.<sup>18</sup> Based on these parameters, insertion loss (IL) is calculated to investigate the performance of this meta-device,<sup>34</sup> which is noted as

IL = 
$$-10 \log [T], \ [T] = |\bar{E}_t|^2 / |\bar{E}_{inc}|^2 = S_0.$$
 (3)

As shown in Fig. 5(a), below 0.92 THz, the insertion loss is relatively low. Particularly, at 0.79 THz, the insertion loss is 0.54 dB, while at 0.91 THz, the half-wave plate presents an insertion loss of 1.25 dB. The simulated results are in agreement with the measured results. The low insertion loss verifies that such anisotropic dielectric metamaterials are promising in designing high efficiency meta-devices. To characterize the performance of the quarter-wave plate, ellipticity is calculated as  $\chi = S_3/S_0$ , which is shown in Fig. 5(b). As can be seen, the measured ellipticity is nearly unity at 0.79 THz, which is in



FIG. 5. Calculated (a) insertion loss, (b) ellipticity, and (c) polarization conversion ratio of the dielectric metamaterials based on the simulation and experimental results.

excellent agreement with the simulated results. This indicates that the incident linearly polarized light is converted into a purely left-handed circularly polarized light. To investigate the performance of the half-wave plate, the polarization conversation ratio (PCR), defined as PCR =  $S_2/S_0$ , is calculated and shown in Fig. 5(c). It is observed in experiments that the PCR is -1 at 0.91 THz, meaning that the incident light polarized at  $\theta = 45^\circ$  to x-axis is converted into a linearly polarized light with the polarization angle of  $\theta = -45^\circ$  to x-axis. Therefore, a dual-functional polarization conversion with high performance is achieved in this meta-device.

In conclusion, we have theoretically proposed and experimentally demonstrated highly efficient terahertz waveplates with all-dielectric metamaterials. Composed of silicon brick arrays, the dielectric metamaterials support electric dipole, magnetic dipole, electric quadrupole, and magnetic quadrupole modes. Through spherical multipole decomposition calculations, we show that these resonances in such an anisotropic design could be engineered and present different multipolar interference effects in different directions, which lead to high transmission and large phase dispersion. As a result, we achieved a highly efficient meta-device that operates as a quarter-wave plate at 0.79 THz and a half-wave plate at 0.91 THz. Such dielectric metamaterials associated with multipolar interference offer a robust approach to design low loss, functional, and compact terahertz meta-devices.

See supplementary material for more details on sample fabrication, measurement procedure, numerical analysis, and discussion.

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