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A pseudo-planar metasurface for a polarization rotator

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Abstract: New demonstrations of effective interaction between light and artificially electromagnetic interface, or the metasurface, have stimulated intensive research interests on control of light to realize applications in beam steering, optical imaging and light focusing, etc. Here we reported a new type of planar metasurface of which every individual metamolecule is single metallic layer with stereo structure and the metasurface is name as Pseudo-Planar Metasurface (PPM). The metamolecule of the PPM is a chiral structure and therefore derives significant optical activity.

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References and links
1. Introduction

Metamaterials, or the artificial electromagnetic media with subwavelength metamolecules, have now become a paradigm for designable electromagnetic properties, e.g. negative refractive index [1, 2], near zero permittivity [3], extraordinary resonant transparency [4] and giant optical chirality [5, 6]. The concept of metamaterials has been applied to vast applications such as optical cloaking [7], super-resolution [8] and perfect absorption [9]. Furthermore, active devices can be realized by using tunable metamaterials [10–12]. Recently, the planar metamaterials, i.e., the metasurfaces, are pushing the metamaterials study to a new breakthrough due to its extraordinary control of light using simple planar texture [13]. For example, wavefront control with phase discontinuity [14] is well demonstrated using metasurfaces with gradient varying metamolecules, which can be used for beam steering [15], optical imaging [16] and beam focusing [17]. However, strong optical activity is difficult to be realized in metasurface due to its weak responses to the magnetic field of the normal incident light.

In recent years metamaterials have been worked on to realize significant optical activity and various metamolecules have been proposed including 3D chiral structure [18], multilayered chiral structure [19, 20] and quasi-2D chiral structure [21], etc. However, in most cases, 3D or multilayered structures are desired for strong optical activity, which inevitably require complex design and fabrication processes. Here, we report a THz metasurface with strong optical activity at normal incidence, which is realized by folding the gammadion-shaped metal surface to introduce the cross-couplings between the electric and magnetic field. The metasurface, consisting of single layered metamolecules with each molecule deflected into a stereo structure, is named as pseudo-planar metasurface (PPM). Similar to 3D chiral metamaterials, the optical activity of the PPM arises from the chiral geometry of the metamolecule, which, therefore, results in a strong and designable optical chirality. Meanwhile, simple fabrication technique is utilized to realize the single layered chiral metamaterials working at THz regime, which can be further extended to infrared part of spectrum. In the experiment, a large polarization rotation at THz regime is measured from the PPM, which is much higher than those in most natural materials in terms of a rotary power per sample thickness in wavelength unit.

2. Design of pseudo-planar metasurface

The metamolecule of the PPM reported here is a metallic gammadion pattern on a trenched surface as shown in Fig. 1(a). The trench is in a square shape and extends into the substrate as an inverted trapezoid body. The gammadion pattern is deposited on the substrate with the center part deflected into the trench which forms a stereo metamolecule. The PPM responses to both electric and magnetic fields of the normal incident light. The deflected gammadion metamolecule is a chiral structure even without the substrate as illustrated in Fig. 1(b). Therefore, a strong optical activity could be derived from such structure. In contrast, a planar gammadion metamolecule without the substrate is achiral as shown in Fig. 1(c). The deflected metamolecule also differs with the multi-layered chiral structure [19] as it induces both the
inductive coupling and the conductive coupling between the metal strips on the top surface and in the trench. Meanwhile, inductive couplings also arises between the metal strips on the side wall of the stereo metamolecule. The proposed structure, although in 3D configuration, can be easily realized by similar fabrication processes of a typical metasurface. The gammadion metamolecule is designed to respond to the terahertz wave, which has a period of 300 µm with side length of the trench top square of 170 µm and different depths \( h \) up to 50 µm.

![Fig. 1. (a) Schematic diagram of the pseudo-planar metasurface. Gammadion metamolecule is deposited on the planar substrate with squared trenches. The center to the metamolecule is deflected in the trench and the metamolecule forms a stereo structure. (b) The stereo gammadion metamolecule on the top is not superimposable with its mirror image at the bottom and is of a chiral structure (c) A planar gammadion metamolecule without the substrate is superimposable with its mirror image, which is an achiral structure.](image)

3. Numerical calculations and discussions

The circularly polarized transmittivity of the PPM is numerically calculated using Finite-difference time-domain (FDTD) method (CST microwave studio) with unit cell boundary condition. The right and left circularly polarized transmittivity, \( t_{++} \) and \( t_{--} \), respectively, are compared at different \( h \) as shown in Fig. 2. No difference is observed between \( t_{++} \) and \( t_{--} \) when \( h = 0 \). Strictly speaking, the planar gammadion on a substrate is indeed a chiral structure due to the symmetry-breaking of the substrate [21]. However, optical activity from this design is too weak to be observed in this frequency region. As \( h \) increases to 10, 20 and 40 µm, \( t_{++} \) and \( t_{--} \) start to distinguish with each other at multi-frequency bands, which indicates the optical activity realization in the PPM. The optical activity of the sample is characterized by the
transmitted polarization rotation angle $\theta$ and ellipticity angle $\chi$, which are related with circular transmittance $t_{++}$ and $t_{-}$ as

$$\theta = (\phi_{++} - \phi_{--}) / 2$$

and

$$\tan \chi = \frac{(t_{++} - t_{--})}{(t_{++} + t_{--})}$$

where $\phi_{++}$ and $\phi_{--}$ are the phase delay of the right circularly and left circularly polarized transmittance, respectively. The value of $\theta$ and $\tan \chi$ are calculated as shown in Fig. 3 for corresponded trench depths. The polarization rotation is increasing as the trench becomes deeper. The rotation angle $\theta$ reaches its maximum at 0.44 THz and 0.56 THz when $h$ is 40 $\mu$m.

![Fig. 2. Numerically calculated right and left circularly polarized transmittivity $t_{++}$ (black line) and $t_{-}$ (red line) when trench depth $h$ is 0, 10 $\mu$m, 20 $\mu$m and 40 $\mu$m.](image)
We analyzed the optical response of the PPM by calculating the amplitude of the electric field distribution inside the PPM when \( h \) is 40 \( \mu \)m. The incident EM wave is polarized along the \( x \) direction at the frequency \( f = 0.56 \) THz, which corresponds to a wavelength of 535 \( \mu \)m. Therefore, the deflection depth of the gammadion structure is less than one tenth of the working wavelength and this metasurface manipulates the incident wave within deep sub-wavelength distance. The \( x \)-oriented and \( y \)-oriented vector components of the electric field in the metasurface are investigated. Figures 4(a) and 4(c) are the amplitude of \( x \)-oriented and \( y \)-oriented electric field in a planar metasurface with the identical size parameters of the PPM, except that the trench depth is 0. Figures 4(b) and 4(d) show the amplitude of \( x \)-oriented and \( y \)-oriented electric field of PPM, respectively. Comparing the electric amplitude at the bottom of the substrate, the \( y \)-oriented field is much weaker than the \( x \)-oriented field for the planar gammadion metasurface, which indicates a trivial polarization conversion. On the other hand, the \( y \)-oriented field is comparable with the \( x \)-oriented field for PPM, demonstrating a large polarization rotation in the four four-folded rotational symmetric structure.
The origination of the polarization rotation is investigated by comparing the surface current of the PPM at 0.47 THz and 0.56 THz as shown in Figs. 5(a) and 5(b), respectively. Large polarization rotation is observed at 0.56 THz while trivial polarization rotation effect is observed at 0.47 THz as shown in Fig. 3(a) when $h = 40 \, \mu m$. The surface current is calculated under linearly polarized incidence oriented in $x$-axis and the red arrows indicate the instantaneous current flow direction. The deflected gammadion can be seen as a structure consisting of two orthogonal deflected “Z” configuration. The surface currents on the two side arms and the center strip are in phase at 0.47 THz for both “Z” component, which is only due to the electric field driving along $x$-direction. No cross-coupling between the electric resonance and magnetic resonance is induced at this frequency. Therefore the polarization rotation is zero. On the other hand, the surface currents on the two side arms and the center strip are out-of phase at 0.56 THz, which can be further interpreted as in Fig. 5(c). The
incident electric field induces an electric dipole \( p \) on the metamolecule and emitted an electric field \( E_p \). Meanwhile, a magnetic dipole \( m \) is also induced on the deflected “Z” structure due to the spiraling surface current, which is similar with that in a helix with only one turn [22]. Both oscillating dipoles reradiate EM waves with electric field \( E_p \) and \( E_m \). The combination of the two reradiated fields is the total scattering field \( E_s \), which is not parallel to the incident \( E_i \) due to the non-zero \( E_m \). Therefore, the transmitted light with the field of \( E_i + E_s \) appears to be rotated from the original \( E_i \).

4. Experimental results and discussions

The pseudo-planar metasurface is fabricated on a Si wafer using a wet etching and lift off processes, which are compatible with massive CMOS fabrication processes. An inversed trapezoid body is first etched out with a taper angle of 54.7° on top of the Si substrate. Photoresist is then sprayed on the substrate and patterned in a gammadion shape concentric with the trench. An aluminum layer is next deposited on the substrate and photoresist layer. Finally lift off process is carried out to remove the unwanted metal part and leaves a gammadion metal structure on the substrate as shown in Fig. 6. The single layered chiral metamaterial has a lattice constant \( P \) of 300 \( \mu m \) and metal slab width \( w \) of 24 \( \mu m \). The scanning electron microscopy (SEM) of the THz metamaterials is shown in Fig. 6(a), which consists of 66 \( \times \) 66 unit cell array and is approximately 2 cm\(^2\) in scale. Figures 6(b) and 6(c) shows a close-up view of the unit cell structure with trench depth of 20 \( \mu m \) and 50 \( \mu m \), respectively.

The optical activity of the sample is characterized by the transmitted polarization rotation angle \( \theta \) and ellipticity angle \( \chi \), which relates to \( t_{\pm} \) and \( t \) as in Eq. (1) and Eq. (2). It is usually difficult to measure the \( t_{\pm} \) and \( t \) due to the lack of corresponding polarizer. Instead, they can be expressed using two orthogonal linear polarized waves as [6]

\[
t_{\pm} = \frac{1}{2} t_{xx} \pm it_{xy}
\]

and \( t_{xx} \) and \( t_{xy} \) can be easily measured by using linear polarizers. Therefore, the optical activity and circular dichroism can be derived by measuring \( t_{xx} \) and \( t_{xy} \). The transmission is measured using TeraView system for different trench depths \( h \). The measured amplitude and
phase of $t_{xx}$ and $t_{xy}$ are converted $t_{xx}$ and $t_{xy}$ using the Eq. (3), which further derive the polarization rotation angle $\theta$ and the ellipticity $\chi$.

The metamaterials are experimentally characterized using TeraView Spectra 3000 in the spectrum between 0.2 THz and 0.7 THz. The terahertz source is linearly polarized in vertical direction which is noted as x-polarization. Dry air is supplied in the measuring chamber to dispel water in atmosphere, which has large absorption in terahertz regime. The transmittivity is of the PPM with trench depth of 0 μm, 10 μm, 20 μm and 50 μm are measured as shown in Fig. 7, the corresponding polarization rotation $\theta$ and ellipticity angle $\chi$ are derived in Fig. 8.

There is no polarization rotation observed when $h$ is 0 at 0.56 THz although it theoretically possesses chirality due to the symmetry-breaking induced by the substrate. The optical activity due to such effect is too weak to be measured. When the trench depth gets increased, the deflected structure itself possesses the chirality even without considering its coupling with substrate. The polarization rotation increases to 2.5°, 5° and 14° when $h$ increases to 10 μm, 20 μm and 50 μm, respectively as shown in Fig. 8(a). Meanwhile, the tangent value of the ellipticity angle $\chi$ also increases from 0 to 0.03 when $h$ increases at 0.58 THz as shown in Fig. 8(b). The increase of the optical activity is due to the enhanced electro-magnetic coupling resulted from the deflected structure. The observed rotation is huge when $h$ is 50 μm, or a height less than 1/10 of the wavelength. In terms of a rotary power per sample thickness in wavelength unit, the PPM rotates the polarization azimuth angle four orders more than that in a quartz crystalline, which is only 21.7°/mm at wavelength of 589 nm [23]. The rotation is also 20 times larger than that in a quasi-2D chiral metamaterial with 1° rotation in a sample of 1/6 wavelength thick [21], and comparable with the giant rotation in some bilayered structures with 28° rotation in a sample of 1/30 wavelength thick [19]. Moreover, the optical activity can be tuned by simply changing the trench depth, which can achieve desired optical activity at arbitrary frequency span. The optical activity is also measured for the stereo gammadion structure different arm length $s$ with fixed trench depth of 50 μm as shown in Fig. 9. There is no optical activity when $s = 0$ because the metamolecule is an achiral structure. As $s$ increases to 50 μm, the metamolecule becomes chiral and weak optical activity is induced. The polarization rotation $\theta$ is 5° at 0.58 THz at this moment and goes on increasing to 14° at

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Fig. 7. Measured right and left circularly polarized transmittivity $t_{++}$ (black line) and $t_{--}$ (red line) when trench depth $h$ is 0, 10 μm, 20 μm and 50 μm.

Fig. 8. The corresponding polarization rotation $\theta$ and ellipticity angle $\chi$ are derived in Fig. 8.
0.56 THz when $s$ is increased to 100 $\mu$m. Therefore, the optical activity can also be controlled by changing the gammadion arm length. In addition, a small shift of polarization rotation peak is observed due to the shift of the electrical resonant frequency which results from the changing arm length.

Fig. 8. The measured (a) polarization rotation angle and (b) ellipticity of the normally incident light with different trench depth $h$. The polarization rotation angle and ellipticity increases as the trench depth increases.

Fig. 9. The measured (a) polarization rotation angle and (b) ellipticity of the normally incident light with different gammadion arm length $s$. The polarization rotation angle and ellipticity increases as the gammadion arm length increases.

5. Conclusions

In conclusions, the pseudo-planar metasurface with single layered stereo metamolecule is demonstrated to have a strong optical activity at THz region with designable rotation power and working frequencies. In the experiment, a 14° polarization rotation is observed at 0.56 THz in a gammadion structure with center deflection of 50 $\mu$m, which corresponds to a huge rotatory power up to 150°/λ. The pseudo-planar metasurface can well control the amplitude, phase and polarization of light and thus offers wide application in as wave-plates, directional antenna and flat lens.

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