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Chiral THz Metamaterial with Tunable Optical Activity

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Abstract

Optical activity in chiral metamaterials is demonstrated in simulation and shows actively tunable giant polarization rotation at THz frequencies. Electric current distributions show that pure chirality is achieved by our bi-layer chiral metamaterial design. The chirality can be optically controlled by illumination with near-infrared light.

1. Introduction

Optical activity, occurring in chiral materials such as DNA, sugar and many other bio-molecules, is a phenomenon of great importance to many areas of science including molecular biology, analytical chemistry, optoelectronics and display applications. This phenomenon is well understood at an effective medium level as a magnetic/electric moment excited by the electric/magnetic field of the incident electromagnetic (EM) wave. Usually, natural chiral materials exhibit very weak optical activity e.g. a gyrotropic quartz crystal [1]. The optical activity of chiral metamaterials, however, can be five orders of magnitude stronger. Chiral metamaterials are made of sub-wavelength resonators lacking symmetry planes. The asymmetry allows magnetic moments to be excited by the electric field of the incident EM wave and vice versa. Recently, chiral metamaterials have been demonstrated and lead to prospects in giant optical activity [1], circular dichroism [2], negative refraction [3-6] and reversing the Casmir force [7]. These fascinating optical properties require strong chirality, which may be designed through the microscopic structure of chiral metamaterials. However, these metamaterials have a fixed response function, defined by the geometric structuring, which limits their ability to manipulate EM waves. Active metamaterials realize dynamic control of response functions and have produced many influential applications such as ultra-fast switching devices [8,9], frequency and phase modulation [10,11] and memory devices [12]. Introducing active designs to chiral metamaterials will give additional freedom in controlling the optical activity, and therefore enable dynamic manipulation of electromagnetic waves. This should prove useful for many potential applications.

In this work, we show an active chiral metamaterial design with tunable giant optical activity. Our numerical simulations show the proposed chiral metamaterial has exceptionally strong polarization rotation with low transmission losses at THz frequencies, which makes it a very efficient material for tunable polarization rotators. Our preliminary experimental results (now shown here) show good agreements with numerical simulations.

2. Method and Results

Our chiral metamaterial is based on double-layer periodic array of unit cells formed by a pairs of conjugated "swastika" shaped metallic structures separated by a dielectric spacer as show in Fig. 1a. The chiral response is provided by the mutual coupling between the co-directed electric and magnetic moments induced by the "U" shaped split-ring resonator (corners of the conjugated-swastika structure) and the double layer short-wire-pair structures [13] (the central part of the conjugated-swastika structure), respectively. The silicon region (red area in Fig. 1a) underneath the bottom layer swastika acts as the active element in the active chiral metamaterial. When the silicon region is illuminated by near-infrared light, its conductivity increases as carries are excited across the 1.12 eV band gap. The silicon region thus becomes a wholly connected metallic square with conductivity σ being a function of the intensity of the illuminating light. As a result, the strength of magnetic resonances is actively controlled by the intensity of illuminating light, which affects the strength of chirality. Thus, by varying the illumination intensity, we are able to control the chirality and the optical activity of the chiral metamaterials.

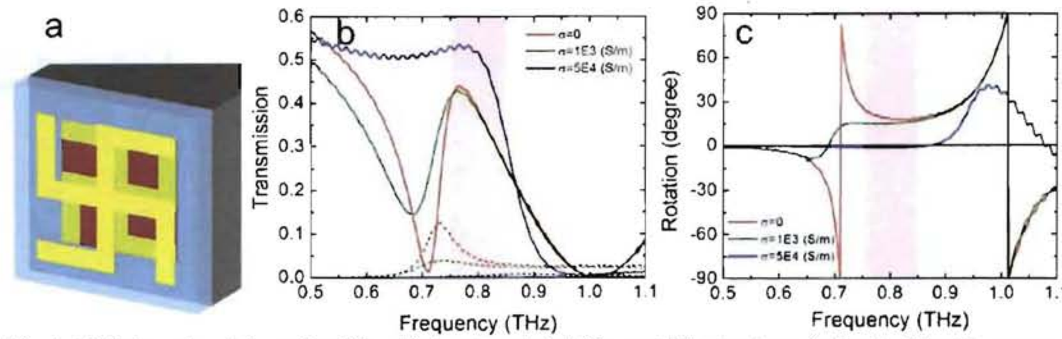

Fig. 1. (a) Schematic of the active THz chiral metamaterial. The metallic structures (yellow), dielectric spacer (blue), silicon layer (red) and dielectric substrate (grey) are shown. (b) Simulated transmission for linear polarizations T_{xx} (solid) and T_{yx} (dashed). Different optically-excited conductivity levels of Si $\sigma=0$ (red), 1×10^3 S/m (green) and 5×10^4 S/m (blue) are shown. (c) Azimuth rotation for linear polarization incidence.

Numerical simulations were performed with CST Microwave Studio (Computer Simulation Technology GmbH, Darmstadt, Germany) using a finite-element method. In the simulations, periodic boundary conditions were applied to a single unit cell shown in Fig. 1a. The metallic swastikas are modelled by gold with conductivity σ_m=4.7×10^7 S/m and have linewidth, w=8 μm, thickness, t=200 nm, and transverse extent, l_t=60 μm and l_b=50 μm, for the top and bottom layer, respectively. The 0.5 μm silicon layer is modelled by a dielectric material with dielectric constant, ε=11.5, and conductivity σ varying from 0 to 5×10^4 S/m to simulate the photoexcitation process under different illumination intensities.

The simulated linear transmission coefficients, T_{xx} and T_{yx}, are shown in Fig. 1b. Two dips in the transmission spectra (solid curves) at 0.65 THz and 1.0 THz correspond to a magnetic and an electric resonance [4,6], respectively. The interesting region is the non-resonant region (red shaded region) between 0.75 and 0.85 THz in Fig. 1b and c, where strong optical activity with high transmission is achieved. The total transmission (i.e., the sum of T_{xx} and T_{yx}) in the shaded region remains above 40%. Moreover, as the conductivity of the silicon layer increases, the cross transmission term, T_{yx}, gradually decreases to zero, indicating the rotation of the polarization direction decreases, which is consistent with the azimuth rotation shown in Fig. 1c.

Fig. 1c shows the azimuth rotation, which measures how much the polarization of the transmitted wave rotates with respect to the incident linearly polarized wave [1,4,6]. As shown in Fig. 1c, in the shadow region between 0.75 to 0.85 THz, the azimuth rotation is around 20° when the conductivity of silicon region is zero. This indicates that the polarization rotates by 20° as the wave propagates through the active chiral metamaterial. Importantly, it remains linearly polarized. As the conductivity of the silicon region increases, the azimuth rotation gradually decreases to zero.

To understand the underlying nature of the chiral metamaterial, we performed detailed studies on the field and surface current distributions. We found that pure chirality was achieved due to the fact that the magnetic/electric moment is induced by the electric/magnetic field (of the incident EM wave) in exactly the parallel direction. Pure chiral metamaterials [1,3-6] are bi-isotropic with eigenpolarizations being circularly polarized waves, in contrast to general bi-anisotropic medium [14] with eigenpolarizations being elliptically polarized waves. Surface current distributions shown in Fig. 2a and b (obtained by numerical simulations) demonstrate the pure chirality. The electric field, $\boldsymbol{E}$, of the incident EM wave induces circular current in "U" shaped parts of swastikas (Fig. 2a), and further results in anti-parallel current (red arrows) in the central parts of the swastikas due to the conjugated arrangement of bi-layer metallic structure. Consequently, a magnetic moment, $\boldsymbol{M}$, anti-parallel to the electric field, $\boldsymbol{E}$, is induced by the anti-parallel currents. On the other hand, the magnetic field, $\boldsymbol{H}$, of the incident electromagnetic wave induces anti-parallel currents [13] (blue arrows as shown in Fig. 2b) in the central parts of swastikas and results in positive and negative charges accumulating in the opposite ends. The time-varying charges generate an electric moment, ***P***, parallel to the magnetic field. Therefore, the magnetic (electric) moment, is excited by the electric (magnetic) field of EM wave in the parallel direction, which results in pure chirality.

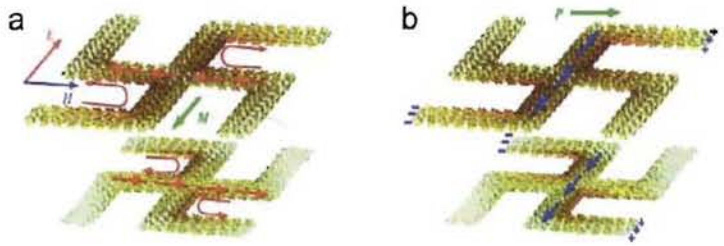

Fig. 2 Surface current distributions of chiral metamaterial obtained from numerical simulations at a frequency where strong optical activity occurs. A magnetic (a), or an electric (b), moment is induced by the electric (a), or the magnetic (b), field of the incident electromagnetic wave in the parallel direction.

3. Conclusion

In summary, we demonstrate numerically that strong optically activity is possible in metamaterials based on double-layered meta-molecules consisting of conjugated planar metal structures. By integrating semiconductor layers into the chiral metamaterial design, we are able to tune the optical activity dynamically, e.g. actively control the polarization angle of the light. The numerical simulations show that active chiral metamaterials can tune the polarization angle of linearly polarized light over a large range (0 to 20°) when stimulated by near-infrared illumination. The tunable chiral metamaterial design enables applications such as polarization controllers and circular polarizers for optoelectronic, life science microscopy and display applications.

References

[1] A. V. Rogacheva, V. A. Fedotov, A. S. Schwanecke, and N. I. Zheludev. "Giant gyrotropy due to electromagnetic-field coupling in a bilayered chiral structure". *Physical Review Letters*, 97,177401, 2006.

[2] J. K. Gansel, M. Thiel, M. S. Rill, M. Decker, K. Bade, V. Saile, G. von Freymann, S. Linden, and M. Wegener,"Gold helix photonic metamaterial as broadband circular polarizer," *Science*, 325, 1513 (2009)

[3] J. B. Pendry. "A Chiral Route to Negative Refraction". *Science*, 306,1353, (2004).

[4] E. Plum, J. Zhou, J. Dong, V. A. Fedotov, T. Koschny, C. M. Soukoulis, and N. I. Zheludev, "Metamaterial with negative index due to chirality", *Physical Review B*, 79, 035407 (2009)

[5] Shuang Zhang, Yong-Shik Park, Jensen Li, Xinchao Lu, Weili Zhang, and Xiang Zhang "Negative Refractive Index in Chiral Metamaterials", *Physical Review Letters* 102, 023901 (2009)

[6] J. Zhou, J. Dong, B Wang, T. Koschny, M. Kafesaki and C. M. Soukoulis, "Negative refractive index due to chirality" *Physical Review B*, 79, 121104 (2009).

[7] R. Zhao, J. Zhou, T. Koschny, E. N. Economou, and C. M. Soukoulis, "Repulsive casimir force in chiral metamaterials," *Physical Review Letters*, 103, 103602, (2009)

[8] W. Padilla, A. Taylor, C. Highstrete, M. Lee, and R. Averitt, "Dynamical electric and magnetic metamaterial response at terahertz frequencies," *Physical Review Letters*, 96, 107401 (2006)

[9] H.-T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor, and R. D. Averitt, "Active terahertz metamaterial devices," *Nature*, 444, 597(2006)

[10] H.-T. Chen, J. F. O'Hara, A. K. Azad, A. J. Taylor, R. D. Averitt, D. B. Shrekenhamer, and W. J. Padilla, "Experimental demonstration of frequency-agile terahertz metamaterials," *Nature Photonics*,2, 295(2008)

[11] H.-T. Chen, W. J. Padilla, M. J. Cich, A. K. Azad, R. D. Averitt, and A. J. Taylor, "A metamaterial solid-state terahertz phase modulator," *Nature Photonics*, 3, 148 (2009).

[12] T. Driscoll, H.-T. Kim, B.-G. Chae, B.-J. Kim, Y.-W. Lee, N. M. Jokerst, S. Palit, D. R. Smith, M. Di Ventra, and D. N. Basov, "Memory metamaterials," *Science*, 325, 1518 (2009).

[13] J. Zhou, L. Zhang, G. Tuttle, T. Koschny, and C. M. Soukoulis, "Negative index materials using simple short wire pairs," *Physical Review B*, 73, 041101 (2006).

[14] N. Liu, H. Liu, S. Zhu, and H. Giessen,"Stereo metamaterials," *Nature Photonics*, 3, 157(2009).