Invited Paper

Manipulating polarization and light propagation using THz metamaterials

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Abstract: The field of metamaterials has been developing rapidly in recent years. Chiral metamaterials and metasurfaces, as promising candidates, hold great advantages and flexibilities to manipulate the polarization state of light. In this talk, we will review THz metamaterial work in our group. We will recall experimental results of manipulating polarization properties using chiral metamaterials in the microwave range. In addition, we review an optically controlled terahertz (THz) switch to tune the state of polarization based on a bilayered chiral metamaterials. The chiral metamaterial consists of an array of perforated slits with incorporated photoactive silicon, which allows us to control dynamically cross-polarization transmission. The switch state can be efficiently controlled by external optical stimuli. The realization of cross-polarization THz switch in the chiral metamaterial has simple structure design and easy fabrication and therefore the proposed chiral metamaterial will be a promising candidate for polarization control devices.

Keywords: THz metamaterial, Metasurface, Photoconductivity, Chirality, Switching

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1. Introduction

Metamaterials can provide a full control of light including its amplitude, phase and polarization [1]. For manipulating polarization properties of wave propagation, great efforts have been devoted to chiral metamaterials. Besides the realization of negative refractive index [2-5], chiral metamaterials can realize giant optical activity [6-18], asymmetric transmission of circularly polarized waves [19-25], optical force [26, 27] and topological phase [28]. Circular birefringence and dichroism are two manifestations of optical activity that does not distinguish between opposite directions of wave propagation. While the asymmetric transmission phenomenon arises from propagation direction-dependent circular conversion dichroism corresponding to reversed right-to-left and left-to-right circular polarization conversion efficiencies for opposite directions of wave propagation. In contrast to the nonreciprocal transmission in the Faraday effect, the asymmetric transmission in chiral metamaterials is reciprocal and fully compliant with the Lorentz's reciprocity theorem. Subsequently, the asymmetric transmission for linearly polarized waves has been studied in multilayered metamaterials from optical to microwave frequencies [29-37]. Especially, many important applications have been reported such as polarization rotators [38, 39], circular polarizers [40-43], absorbers [44, 45], chiral switching [46, 47] and polarization spectrum filters [48, 49].

Here, we review THz metamaterial work in our lab. We have designed a bilayered chiral metamaterial having the cross-polarization conversion properties and asymmetric transmission phenomenon. In the microwave range, the cross-polarization conversion efficiency is more than 90% and relative bandwidth of asymmetric transmission is larger than 50% [37]. Further, we have demonstrated a kind of optically controlled terahertz switching based on the cross-polarization conversion [47]. The simulation results manifest that the hybridized chiral metamaterial allows us to effectively tune the cross-polarization transmission by controlling external optical stimuli, and the tunability of the resonant frequencies between resonances I and II is about 11%.

2. Chiral metamaterials and polarization manipulation [37, 47]

Asymmetrically split ring (ASR) meta-molecules are important building blocks of metamaterial structures [9, 11, 17]. The Babinet principle can be applied to design the planar chiral metasurface. The Babinet-inverted metasurface consists of an array of asymmetrically split ring apertures (ASRA) that are exactly complementary to asymmetrically split rings. Especially, the bilayered metasurfaces are geometrically identical, but are arranged with a twist angle of 90 ° in order to give birth to a strong chirality due to the near-field magnetic and electric coupling. Our metasurface consists of an array of square stereo ASRA dimers [37]. Each stereo ASRA dimer consists of two spatially separated coaxial ASRAs, which are structural identical but the back layer is twisted by 90 ° with respect to the front one. Each ASRA consists of two different arc slits corresponding to open angles 160 ° and 100 °. For the forward propagation along –z direction, the co-polarization transmission t_{xx} and t_{yy} are always identical and exhibit three resonant peaks below 0.1. In contrast to co-polarization transmission, the cross-polarization transmission t_{xy} is extremely different from t_{yx}, indicating the presence of the asymmetric transmission effect for linearly polarized waves and the absence of the asymmetric transmission effect for circularly polarized waves in the proposed chiral metamaterial. The experiments are carried out in an anechoic chamber using broadband horn antennas and a vector network analyzer. In the broad frequency range of 5.5-10 *GHz*, the measured intensity transmission contrast between t_{xy}^2 and t_{yx}^2 is always larger than 17.7 *dB*. We can obtain the relative bandwidth larger than 50% for a good asymmetric transmission. In this broad pass band, for the forward propagation, incident *y*-polarized wave can pass through the metamaterial slab and then completely converted to *x*-polarized wave while incident *x*-polarized wave is completely blocked.

Further, we have developed a multi-band background-free terahertz (THz) switch in photoactive chiral metamaterial using polarization conversion. Such ultrathin switchable THz metamaterial is constructed by an array of 90 °-twisted asymmetrically split ring apertures (ASRA) with being incorporated photoconductive silicon. According to Ref. 47, the anisotropic chiral metamaterial enables a broadband polarization conversion, with the co-polarization transmission being totally suppressed. The hybridized chiral metamaterial allows us to effectively tune the cross-polarization transmission by controlling the conductivity of the active material using external optical stimuli. The metamaterial structure is similar to the one in Ref. 37. The period of perforation is d=100 μm. The two ASRAs are spatially separated by a dielectric thin layer polyimide with a thickness of t=16 μm Each ASRA consists of two different arc slits corresponding to open angles α=90° and β=160°, as shown in Fig. 1(a). The radius of the ASRA is r=42.5 μm and the split width is w=10 μm. In order to realize an active THz metamaterial, silicon is incorporated into two short apertures of α=90 °. The thickness of silicon is identical to that of gold films, i.e. 200 *nm*. Under external optical stimulus, silicon incorporated into the chiral metamaterial will exhibit an insulator-to-metal transition due to the excitation of the semiconductor carrier, thus modulating the associated cross-polarization transmission.

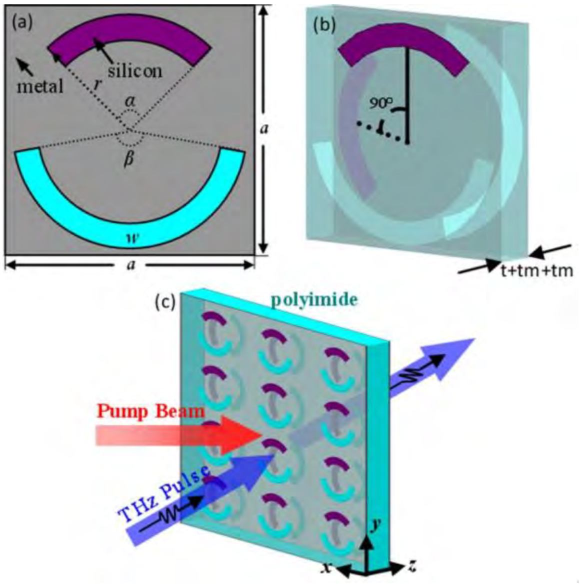

Fig. 1 Schematic of an active THz metamaterial switch. (a) The front view of a unit cell in the bilayered chiral metamaterial. (b) The stereogram of a unit cell. (c) Schematic principle of the optically controlled THz switch based on polarization conversion. Photoconductive silicon (purple part) is filled into two short apertures of the gold film (gray part) and the dielectric spacer is polyimide (light blue part). Reproduced from Ref. 47

Figures 2(a) and 2(b) show the simulated optically controlled cross-polarization and co-polarization transmission spectra of the proposed THz metamaterial switch for the y-polarized wave propagating along z direction, respectively. The different conductivity values can be used to model the increasing intensity of external optical stimuli. In Fig. 2(a), σ_{si} may be seen as 1 *S/m* lacking of light illumination. For the cross-polarization transmission, three resonant peaks occur around at the frequencies of 0.90 *THz*, 1.16 *THz* and 1.52 *THz*. Resonance III has a transmission maximum $|t_{xy}|$ = 73.7%, while resonances I and IV have an intermediate cross-polarization transmission $|t_{xy}|$ = 55.2% and $|t_{xy}|$ = 61.9%, respectively. As the conductivity of silicon increases, resonances I and IV rapidly weaken and eventually vanish, while resonance III slowly weakens. Obviously, both resonances I and IV are in the "OFF" state when the THz metamaterial is illuminated by strong optical pump. When σ_{si} exceeds 40000 *S/m*, corresponding to the level with energy flux 155 *μJ/cm*2 for optical pump, a pronounced resonance II emerges at 1.00 *THz*. As σsi further increases, the cross-polarization transmission is up to 54.2% and resonance II is in the "ON" state. At resonance III, the cross-polarization transmission increases and reaches 70.7% for strong pump, equivalent to the case of no pump. All resonant frequencies remain unchanged regardless of optical pump. Specially, the THz metamaterial exhibits a photoexcited mode-switching effect between resonances I and II and a tunability of the resonant frequency is about 11%. More importantly, the co-polarization transmission is totally suppressed below 1% in the frequency range of 0.7-1.7 *THz* due to the orthogonal arrangement of bilayered structures regardless of optical pump, shown in Fig. 2(b). Therefore, the transmitted wave in our proposed metamaterial exhibits relatively high purity of polarization that is different from input signal and optical background, which is also verified by the polarization rotation angle and ellipticity in Fig. 2(c).

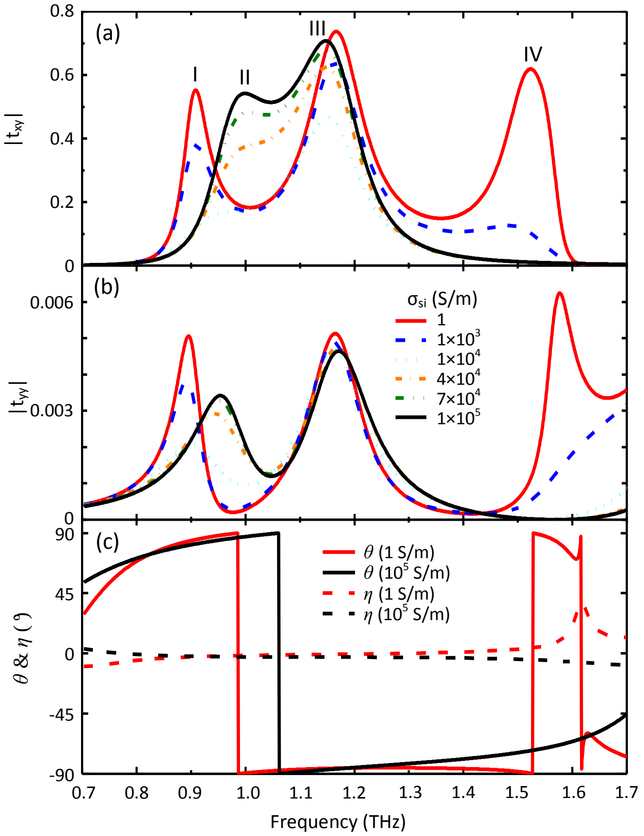

Fig. 2 Simulated transmission spectra of THz metamaterial switching. (a) Cross-polarization transmission $|t_{xy}|$ and (b) co-polarization transmission $|t_{yy}|$ as a function of silicon conductivity. (c) Simulated polarization rotation angle θ and ellipticity η. Reproduced from Ref. 47.

3. Conclusions

Chiral metamaterials and metasurfaces, as promising candidates, hold great advantages and flexibilities to manipulate the polarization state of light. In this talk, we have reviewed THz metamateial work in our group. We have recalled experimental results of manipulating polarization properties using chiral metamaterials in the microwave range. In addition, we have reviewed an optically controlled terahertz (THz) switch to tune the state of polarization based on a bilayered chiral metamaterials. The chiral metamaterial consists of an array of perforated slits with incorporated photoactive silicon, which allows us to control dynamically cross-polarization transmission. The switch state can be efficiently controlled by external optical stimuli. The realization of cross-polarization THz switch in the chiral metamaterial has simple structure design and easy fabrication and therefore the proposed chiral metamaterial will be a promising candidate for polarization control devices.

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