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Electrical control of terahertz polarization by graphene microstructure

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ABSTRACT

In this letter, we proposed and numerically analyzed an electric controlling polarization modulator of the terahertz wave, which is composed of a graphene monolayer microstructure with an L-shaped nanoholes array. The graphene microstructure is employed to excite the plasmonic dipolar and quadrupolar resonances in terahertz region. Through the superposition of the cross-polarized wave radiated by these plasmonic resonances, the polarization rotation effect can be obtained. Utilizing the capacitor doping, the rotation angle can be controlled by the external applied voltage, thus achieving a tunable polarization modulator.

1. Introduction

Polarization is an import characteristic of light due to many phenomena inherently polarization sensitive. The capability of manipulating the polarization state is of high interest for many applications such as polarization controllers, life science microscopy, display applications, etc. Conventional polarizer can be realized using anisotropic media, or employing the Brewser amd birefringence effect, but with specific thickness limitations and quite bulky configurations [1]. These polarizing components are not easily integrated with photonic circuits. In order to realize the miniaturization of the devices, some micro-structures, such as artificial planar chiral structures [2–6], plasmonic crystals [7], and other planar nonchiral metamaterials [8,9], have been widely investigated experimentally and theoretically. However, the optical rotation angle is dominated by the geometric parameters of the sample structures. It is difficult to conveniently control optical rotation through the external operations. On the other hand, graphene is an atomically thin, two-dimensional carbon material, whose conduction and valence bands meeting at the Dirac point, emboding unique electrical [10], optical [11], and mechanical [12] properties. Graphene can be doped to high values of electron or hole concentrations by applying voltage externally on a field-effect transistor (FET) [13], leading to the changes of its optical properties. Hence graphene is a very attractive candidate for controlling optical properties by applying external field. Although researches in graphene have been conducted on optical polarization properties such as optical Faraday rotation in graphene layer [14], microribbons [15], periodic structure [16], and broadband fiber polarizer based on graphene [17], electrical control of optical polarization has not been investigated. For the purposes of this study, we try to seek for the method of external voltage controlling optical polarization.

Plasmons describe collective oscillations of electrons. They offer a collection of techniques to tame the electromagnetic fields into desired functionalities, and form the basis of research into optical metamaterials [18,19]. For example, optical rotations can be produced by the coupling of the excited plasmonic resonances via the strongly enhanced local electric fields [20,21]. Graphene can sustain plasmonic resonances in the mid-infared and THz regime. Its plasmonic resonance frequency depends on the concentration of charge carriers, which can be electrically adjusted by a bias voltage applied on the FET [22–28]. In this paper, we designed a graphene monolayer structure with an L-shaped nanoholes array, on which the plasmonic dipolar and quadrupolar resonances can be excited, leading to an optical rotation effect. Through a bias voltage modulating the plasmonic resonance frequency, we realized the electrical control of terahertz wave polarization in theory.

Our designed graphene structure is shown in Fig. 1. A graphene monolayer with an L-shaped nanoholes array is placed on the 100 nm thick aluminum oxide film, which is deposited on the p^+ doped silicon substrate. The width and length of L-shaped nanohole arms are 30 and 100 nm, respectively. Its period is 200 nm. A linearly x-polarized terahertz wave is incident normally to the

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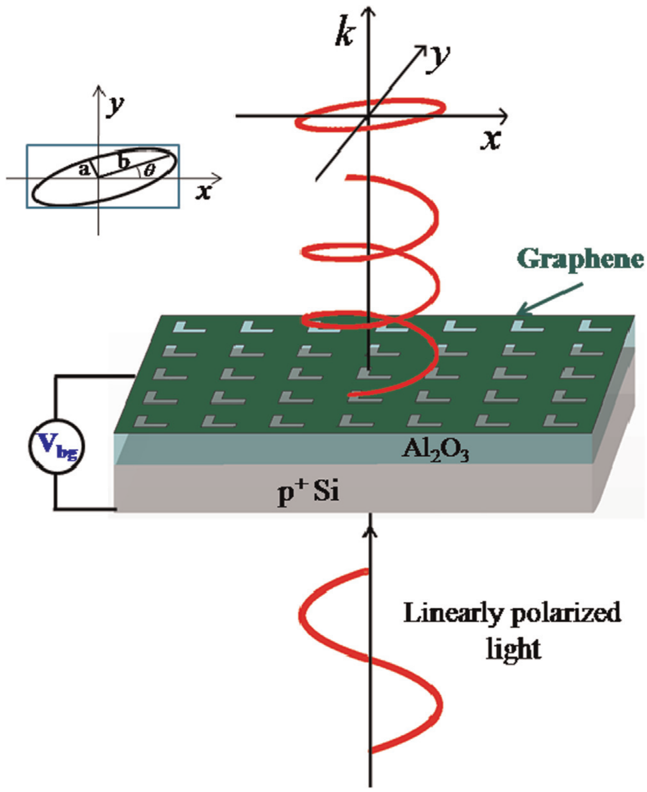

Fig. 1. Schematic of the proposed graphene microstructure, which is composed of a p^+Si substrate, a spacer layer of aluminum oxide and a graphene monolayer with an L-shaped nanoholes array. The inset represents the transmitted elliptical polarization state, where a and b indicate the short and long semi-axes of the polarization ellipse, respectively, and θ shows the polarization rotation angle.

sample plane. The polarization of the transmitted wave with the applied voltage V_{bg} between the graphene sheet and the back-gated p^+Si is investigated by using the Lumerical FDTD solutions based on the finite-difference time-domain method. In calculation, the permittivity of graphene is expressed by $\varepsilon_g = -\sigma_{g,i}/\omega t + i\sigma_{g,r}/\omega t$ [29], where $\sigma_{g,i}$ and $\sigma_{g,r}$ are the imaginary and real part of the conductivity of graphene σ_g, respectively, and t is the thickness of graphene. Here, the thickness t is taken as 0.5 nm. At THz frequencies, the conductivity σ_g can be described by a Drude-like expression $\sigma_g = i(e^2E_f/\pi\hbar^2)/(\omega + i\tau^{-1})$ [22,24], where E_f and τ represent respectively the Fermi energy level and the carrier relaxation time of graphene and are given by $\hbar v_f(\pi n_g)^{1/2}$ and uE_f/ev_f^2 [22] with the Fermi velocity $v_f \approx 10^6$ m/s and the carrier mobility $u \approx 10{,}000\ \mathrm{cm^2/(V\,s)}$. The carrier concentration n_g can be induced by the capacitor, $n_g = \varepsilon_0\varepsilon_r V_{bg}/ed$, here ε_r and d is the permittivity and thickness of aluminum oxide layer which is taken as 3.0976 and 100 nm, respectively.

Fig. 2(a) shows the calculated cross-polarized transmitted spectra, where the transmittance T_{ij} corresponds to the j-polarized wave in and i-polarized wave out. Here, the applied voltage is taken as 29 V, and thus the Fermi energy level E_f is 0.2593 eV. There are two dips at frequencies 15.03 THz (labeled by A) and 19.58 THz (labeled by B) in the transmitted spectrum T_{xx}, whose transmittances are 76% and 89%, respectively. In order to reveal their physics origin, we calculated the corresponding electric field E_z distributions at the air–graphene interface shown in the inset of Fig. 2(a). From the alternating electric field distribution on the four hole-walls, we can infer that the dips A and B are induced by the plasmonic dipolar and quadrupolar resonances [30,31]. Due to broken symmetry of the structures, when the localized plasmonic resonances are excited, the induced charges would be displaced

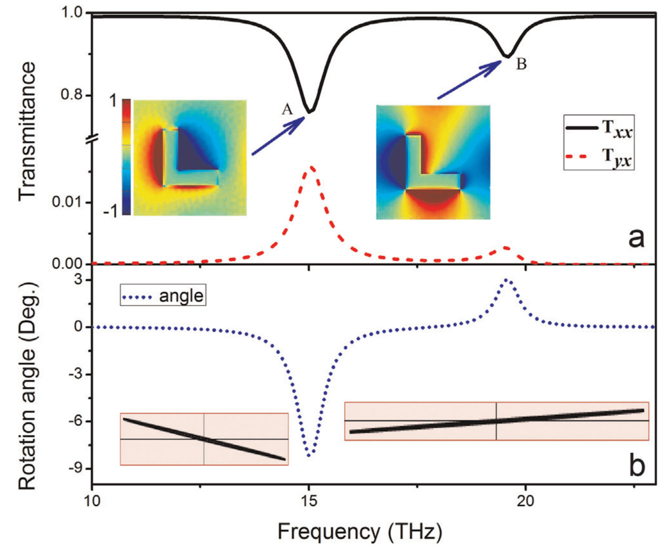

Fig. 2. (a) is the calculated cross-polarized transmission T_{xx} (black solid line) and T_{yx} (red dash line). Insets of (a) are the electric field E_z distributions at dips A (left) and B (right) in the air–graphene surface. (b) shows the polarization rotation angle with the frequency. Insets of (b) plot the polarized states of transmitted terahertz waves at dips A (left) and B (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

not only along the direction of the incident field, but also into another direction through the bent corner, thereby resulting in a charge oscillation perpendicular to the driving electric field [20]. As can been also seen from the electric field distributions (inset of Fig. 2(a)). Thus the cross-polarized electromagnetic waves radiated by the charge oscillation are obtained. Its transmitted spectrum T_{yx} is shown in Fig. 2(a). Corresponding to the dips A and B of T_{xx}, there are two transmitted peaks in T_{yx} with 1.6% and 0.3% of transmittances. Based on superposition principle, the polarized state of transmitted wave through the sample can be obtained by using the well-known equation

$$\frac{x^2}{E_{xx}^2} + \frac{y^2}{E_{yx}^2} - 2\frac{xy}{E_{xx}E_{yx}}\cos\delta = \sin^2\delta, \tag{1}$$

where E_{xx} and E_{yx} are the electric field components along x and y direction radiated by the plasmonic dipolar (quadrupolar) resonances, and δ is their phase difference. In general, a linearly polarized wave transmitted through the structure will become elliptical. Its ellipticity is defined by the ratio of the short and long semi-axes of the polarization ellipse (see inset of Fig. 1). The rotation (azimuth) angle θ defined by the angle between the long-axis of ellipse and x-axis can be obtained by

$$\tan 2\theta = \frac{2E_{xx}E_{yx}}{E_{xx}^2 - E_{yx}^2}\cos\delta, \tag{2}$$

Fig. 2(b) shows the polarization rotation angles with the frequencies. For the plasmonic dipolar (dip A) and quadrupolar (dip B) resonances, the polarization rotation angles are $-8.2°$ and $3.1°$, respectively, which are larger than that in Faraday rotation of graphene [14,15]. Their corresponding ellipticities are 0.008 and 0.005, respectively, which are close to linearly polarized states [insets of Fig. 2(b)].

An important factor determining the characteristics of transmission efficiencies and the degree of polarization rotation is the carrier concentration of graphene monolayer when the external bias is applied. The increase of the polarization rotation will be associated with the carrier concentration due to charges injected into the graphene layer. Thus, we try to investigate the dependences of polarization rotation angles on the applied voltage