Broadband tunable terahertz polarization converter based on graphene metamaterial

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ABSTRACT

We design and numerically investigate a broadband tunable terahertz polarization converter based on graphene metamaterial. The converter presents a broad conversion band with high polarization conversion ratio (>0.95) in terahertz frequency over a bandwidth which is 25.8% of the central frequency. The converter can be dynamically tuned by varying the Fermi Energy of the graphene without changing the geometric structure. The converter shows high conversion ratio for a wide range of incident angles from 0 to 40°. By the scaling of the proposed structure, the broadband properties of the converter can be easily spread to other frequency. The proposed metamaterial offers an approach in the manipulation of the light polarization and has potential applications in imaging, sensing and communications.

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1. Introduction

Polarization is a fundamental property of electromagnetic waves. Manipulating the polarization of electromagnetic waves is of practical importance in many areas such as imaging, sensing and communications [1,2]. The conventional methods to manipulate the polarization include using optical gratings and birefringence materials [3,4]. However, these methods usually use long distance to obtain phase accumulation and need bulky volume. In recent years, metamaterial has attracted much attention due to its extraordinary optical properties and applications such as negative refraction, sub-diffraction imaging and invisible cloaking [5–7]. Many polarization converters based on metamaterial structures have been proposed from microwave region to visible region [8–12]. These converters are usually realized by metallic nanostructure. However, most of these structures can be tuned only by changing geometric parameters of the structures. The applications of the structures are limited and active control of the spectral response is needed.

Graphene, a two-dimensional layer of carbon atoms arranged in honeycomb pattern, has attracted remarkable attention in plasmonics due to its unique properties such as electrical tunability, strong field confinement and low losses [13–15]. It is found that graphene conductivity can be dynamically controlled in the terahertz frequency by changing the Fermi energy level based on chemical doping or electrostatic gating [16,17]. Many tunable devices based on graphene plasmon have been investigated such as sensors [18,19], switches [20,21] and modulators [22,23]. Photodetectors [24], absorbers [25–27] and plasmon-induced transparency devices [28] based on graphene metamaterials have also been proposed. In order to control the polarization of light, many polarization converters based on patterned graphene metamaterials have been proposed [29–38]. However, most of these converters work with narrow bandwidth or low efficiency. T. Guo et al. designed a broadband polarizer based on L-shaped graphene metasurface, but the polarization conversion ratio was limited [31]. H. Cheng et al. designed tunable infrared polarization converters based on cross-shaped graphene metamaterial, but the bandwidth was limited [39]. C. Yang et al. designed a wideband tunable cross polarization converter using rectangle-shape perforated graphene with a band 5% of the central frequency [32]. Broadband polarization converter with high efficiency is needed.

In this work, we present a broadband tunable terahertz polarization converter based on graphene metamaterial which is composed of cross-shaped structure. A broad conversion band with high polarization conversion ratio from 6.68 THz to 8.66 THz is achieved by the converter. The converter keeps high conversion ratio for a wide range of incident angles and can be dynamically tuned by varying the Fermi Energy of the graphene. We investigate the influence of the structure parameters on the optical properties in detail.
2. Structure and numerical simulations

The schematic geometry of the proposed structure is shown in Fig. 1. As shown in Fig. 1(a), the unit cell of the structure is composed of two perpendicular graphene rectangles marked as Rec1 and Rec2 respectively, as shown in Figs. 1(b) and 1(c). The orientation of the rectangles Rec1 and Rec2 are 45° along the x and y direction. The unit cells are arranged periodically both in x and y directions while the perfect match layer (PML) boundary conditions are imposed at the boundaries in z direction. The cross-shaped graphene structure is composed of two perpendicular graphene rectangles marked as Rec1 and Rec2 respectively, as shown in Figs. 1(b) and 1(c). The orientation of the rectangles Rec1 and Rec2 are 45° along the x and y direction. The unit cells are arranged periodically both in x and y directions with \( p_x = p_y = p = 2 \mu m \). Optimized structural parameters are as follows: \( L_1 = 2 \mu m, L_2 = 1.5 \mu m, w = 0.6 \mu m, t = 6.5 \mu m \). With random phase approximation (RPA), the surface conductivity of monolayer graphene can be given by using Kubo formula, including interband and intraband contributions [40]

\[
\sigma(\omega) = \frac{i e^2}{\hbar^2} E_F \left( \frac{\omega}{\omega + i \tau^{-1}} \right) + \frac{i e^2}{4 \hbar^2} \ln \left( \frac{2 E_F + h (\omega + i \tau^{-1})}{2 E_F - h (\omega + i \tau^{-1})} \right)
\]

In the THz region, the intraband contribution dominates and the surface conductivity can be simplified as \( \sigma(\omega) = \frac{i e^2}{\hbar^2} \frac{E_F}{\omega + i \tau^{-1}} \), where \( e \) is the electron charge, \( h \) is the reduced Planck constant, \( E_F \) is the Fermi level of graphene, \( \omega \) is the angular frequency. The carrier relaxation time \( \tau \) is defined as \( \tau = \frac{\mu E_F}{e v_F^2} \), where \( \mu \) is the carrier mobility and \( v_F \approx c/300 \) is the Fermi velocity.

According to previous reports, high mobility of graphene has been achieved by experiment. J. A. Robinson et al. [41] have achieved high mobility of 18,100 cm²V⁻¹s⁻¹ for graphene on SiC and J. H. Chen et al. [42] have achieved a graphene film on a SiO₂ substrate with mobility of 40,000 cm²V⁻¹s⁻¹ at room temperature. In our simulation, we set the mobility to 10,000 cm²V⁻¹s⁻¹ as a moderate value which is not difficult to realize.

The finite difference time domain method based on FDTD solutions is employed to perform the numerical simulations. The graphene is regarded as a two dimensional layer and we use surface conductivity to model it. In the three-dimensional simulations, periodic boundary conditions are applied in the x and y directions while the perfect match layer (PML) boundary conditions are imposed at the boundaries in z direction. Here, we choose gold as the material of the metallic layer and the permittivity of gold is taken from [43]. The dielectric constant of the dielectric layer SiO₂ is set to be 2.25. A normally incident plane wave along the z direction polarized along the x direction is applied. In order to describe the reflection characteristics of the converter, the reflection coefficients are defined as \( R_{ij} = |E_{rec}^i/E_{inc}^i| \), where \( E_{inc} \) and \( E_{rec}^i \) donate the incident and reflected light respectively. The subscripts x and y donate the polarization direction of the light. The polarization conversion ratio (PCR) is defined as \( PCR = |R_{xx}|^2/(|R_{xx}|^2+|R_{xy}|^2) \) [9].

3. Results and discussions

In order to better understand the properties of the proposed polarization converter, we firstly present the simulation results of the separated structures shown in Figs. 1(b) and 1(c). The resonant frequencies for the structures shown in Figs. 2(a) and 2(b) are 6.05 THz and 8.14 THz respectively. We can observe a dip in \( R_{xx} \) and a peak in \( R_{xy} \) at the resonant frequency. Due to the symmetry of the structure, the only difference between the two rectangular structures is the length of the rectangle. The resonant frequency is shifted to higher frequency when the length of the rectangle decreases and this is useful for the design of the cross-shaped strips structure. The PCR of the two rectangular structures are shown in Fig. 2(b). The PCR is higher than 0.95 from 5.90 THz to 6.23 THz for Rec1 and 7.99 THz to 8.29 THz for Rec2. It indicates that a linearly polarized light converts into its cross polarized light at a narrow frequency range by the converter composed of the rectangular structure. The electric field distributions at the resonant frequencies are shown in the inlets of Fig. 2(b). We can see that the fields are concentrated on the corners of the rectangle and a clear dipolar resonance can be observed.

Fig. 3 shows the simulated result for the cross-shaped structure. As shown in Fig. 3(a), the reflection coefficient \( R_{xy} \), keeps a high value over a broad frequency range. The PCR is higher than 0.95 at the frequency range from 6.68–8.66 THz which presents a broadband polarization converter as shown in Fig. 3(b). The bandwidth is 25.8% of the central frequency. The phase difference between \( R_{xx} \) and \( R_{xy} \) is also shown in Fig. 3(b).

In order to understand the underlying physics of the broadband conversion, the electric field distributions at the resonant frequency of the cross-shaped structure are calculated and presented in Figs. 4(a)–4(c). Figs. 4(a) and 4(c) are the field distributions at the resonant frequency of 8.14 THz. As shown in Fig. 4(a), the electric field at the resonant frequency is shown in the inset. The field is concentrated around the corner of the rectangle. In Fig. 4(c), the electric field is concentrated around the line connecting the two opposite corners of the rectangle. The field distribution at 6.05 THz is shown in Figs. 4(b) and 4(d). The field is concentrated around the corner of the shorter rectangle in Fig. 4(b) while it is around the longer one in Fig. 4(d). The field distribution at 7.99 THz is shown in Figs. 4(c) and 4(d). The field is concentrated around the corner of the shorter rectangle in Fig. 4(c) while it is around the longer one in Fig. 4(d).
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