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Terahertz modulation based on surface plasmon resonance by self-gated graphene

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ABSTRACT

We theoretically and numerically investigate the extraordinary optical transmission through a terahertz metamaterial composed of metallic ring aperture arrays. The physical mechanism of different transmission peaks is elucidated to be magnetic polaritons or propagation surface plasmons with the help of surface current and electromagnetic field distributions at respective resonance frequencies. Then, we propose a high performance terahertz modulator based on the unique PSP resonance and combined with the metallic ring aperture arrays and a self-gated parallel-plate graphene capacitor. Because, to date, few researches have exhibited gate-controlled graphene modulation in terahertz region with low insertion losses, high modulation depth and low control voltage at room temperature. Here, we propose a 96% amplitude modulation with 0.7 dB insertion losses and ∼5.5 V gate voltage. Besides, we further study the absorption spectra of the modulator. When the transmission of modulator is very low, a 91% absorption can be achieved for avoiding damaging the source devices.

1. Introduction

A great number of experimental and theoretical studies have confirmed the extraordinary optical transmission (EOT) effect of periodic subwavelength structure on a metallic layer in the terahertz (THz) region [1]. And surface plasmon (SP) resonance excited at the interface between metal and dielectric plays a crucial role in the EOT phenomenon [2]. According to the different resonance properties, SP can be categorized into propagation surface plasmons (PSP) [3] and localized surface plasmons (LSP) [4,5]. Lu et al. [6] explained LSP in the periodic arrays of subwavelength metallic ring and coaxial ring-disk structures. Xia et al. measured a metal–dielectric–metal structure with subwavelength air ring apertures in two metallic layers and explained theoretically the observed EOT peaks of PSP and LSP modes by the dispersion relation [7].

Graphene is a two-dimensional carbon nanomaterial with zero bandgap, which has recently been exploited for THz applications due to its extraordinary mechanical, thermal and electrical characteristics. It uniquely possesses linear dispersion for electrons close to Dirac point, high carrier mobility and high Fermi velocity $V_F = 10^8$ cm/s [8]. At THz and infrared frequencies, the carrier density in a graphene sheet can be changed by chemical or electronic doping over a large rang, which modifies its Fermi level and makes it a promising platform for modulators [9], absorbers [10], plasmonic devices [11,12] and electromagnetic cloaks [13]. For instance, Lee et al. demonstrated terahertz wave switching composed of single-layer graphene on top of a hexagonal unit cell metamaterial [14]. The gate-controllable light–matter interaction in the graphene can be enhanced by the strong resonance of meta-atoms, which allows persistent switching and modulation of both the amplitude and phase up to 47% and 32.2°, whereas the insert losses and the applied gate voltage are too large. A broadband electroabsorption modulator with modulation depth ∼76% and operational bandwidth ∼55% was proposed by utilizing the Fabry–Perot oscillations which create a spectral response of the electric field at the graphene layer that compensates the dispersion of the graphene conductivity [15]. Because the modulator is based on metal reflection structure to achieve enhanced modulation, the modulation should be realized in the reflection spectrum and the gate voltage is ∼53 V, which may be inconvenient for terahertz applications. Gao et al. demonstrated an active amplitude modulation with gate-controlled graphene by EOT effect through metallic ring apertures [16]. A ∼50% modulation depth with ∼2 dB insert losses can be realized under gate voltages from −20 V to +20 V. An active diode consisting of a graphene–silicon hybrid film for terahertz modulation was reported through simultaneous optical and electrical excitations [17].

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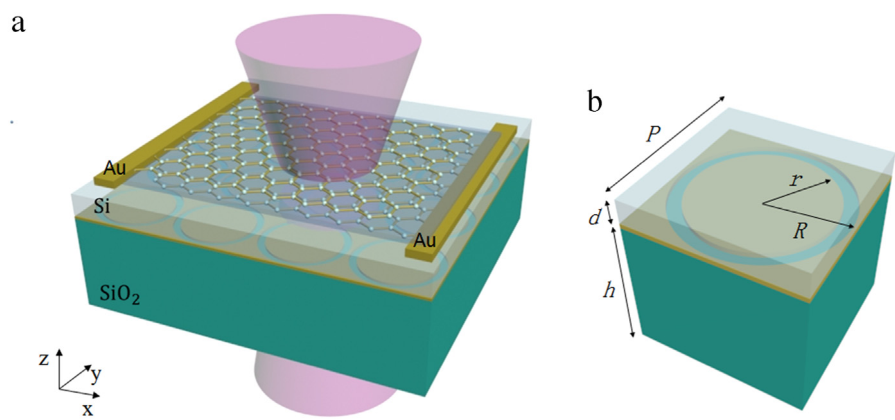

Fig. 1. (a) Schematic diagram of the GMTM. (b) One unit cell of the DMD structure and geometry parameters.

In this paper, we theoretically demonstrated the different EOT peaks of a dielectric–metal–dielectric (DMD) structure with subwavelength ring aperture arrays by means of magnetic polaritons (MP) [18] and PSP. When the DMD structure combines with the novel reconfigurable graphene, we propose a graphene metamaterial terahertz modulator (GMTM) with low insertion losses, low gate voltage and high modulation depth by optimizing the structure. Furthermore, when the power transmission of GMTM is very low, it is available to achieve a high power absorption as well as low return losses.

2. Structure and simulation method

Fig. 1(a) shows the schematic of the proposed GMTM, which consists of a square lattice of two chemically vapor deposited graphene monolayers separated by a thin ($h_{ox} \sim 100$ nm) aluminum oxide (Al_2O_3) layer with relative permittivity $\varepsilon_{ox} = 9.6$, and the DMD structure composed of a metallic EOT structure and a $d = 20$ μm thick silicon (Si) overlayer with $\varepsilon_1 = 12.11$. The dielectric substrate is quartz (SiO_2) with $\varepsilon_2 = 3.61$ and thickness $h = 85$ μm. The gate voltage is applied between the two graphene layers by the Au electrodes. The incident terahertz wave normally transmits through the GMTM along z direction. One unit cell of the DMD structure is shown in Fig. 1(b). It is periodically arranged along the x and y directions with the periodicity $P = 76.4$ μm. Ring aperture arrays can be fabricated on the ∼1 μm thick Ag metallic layer with external radius $R = 38$ μm and internal radius $r = 32$ μm.

Graphene can be characterized by its surface conductivity, which is modeled using the Kubo formalism [19] as

$$\sigma(\omega,\mu_C,\Gamma,T) = \frac{-ie^2(\omega+2i\Gamma)}{\pi\hbar^2} \times \left[\frac{1}{(\omega+2i\Gamma)^2}\int_0^\infty \varepsilon\left(\frac{\partial f_d(\varepsilon)}{\partial\varepsilon} - \frac{\partial f_d(-\varepsilon)}{\partial\varepsilon}\right)d\varepsilon - \int_0^\infty \frac{f_d(-\varepsilon)-f_d(\varepsilon)}{(\omega+2i\Gamma)^2-4(\varepsilon/\hbar)^2}d\varepsilon\right] \tag{1}$$

where $f_d = 1/(1+\exp[(\varepsilon-\mu_c)/k_B T])$ is the Fermi–Dirac distribution, ω is radian frequency, μ_c is the graphene chemical potential, Γ is the scattering rate, e is the electron charge, $\hbar$ is the reduced Planck's constant, k_B is the Boltzmann's constant, T is the temperature. The first term in Eq. (1) corresponds to the intraband electron–photon scattering process and the second term corresponds to the direct interband electron transition. In our study, we use here a constant value of $\Gamma = 0.47$ meV, which is consistent with the ballistic transport features of graphene.

In addition, the carrier density n_s and chemical potential μ_c of the graphene is related through

$$n_s = \frac{2}{\pi\hbar^2 V_F^2}\left[(k_B T)^2\int_{-\mu_c/k_B T}^{\mu_c/k_B T}\frac{x}{e^x+1}dx + k_B T\mu_c \ln\left(e^{-\frac{\mu_c}{k_B T}}+1\right) + k_B T\mu_c \ln\left(e^{\frac{\mu_c}{k_B T}}+1\right)\right]. \tag{2}$$

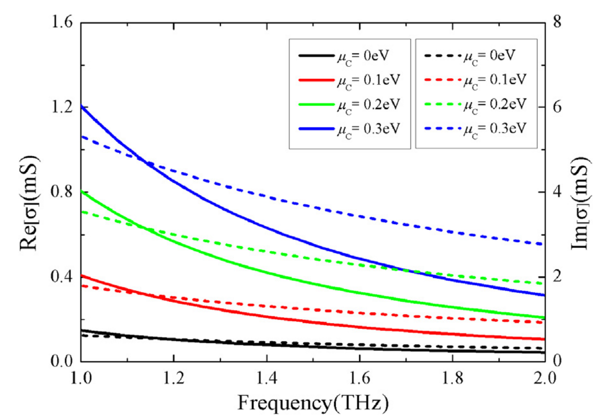

Fig. 2. Calculated graphene conductivity as a function of the chemical potential and frequency. The solid and dashed lines correspond to the real and imaginary parts of σ, respectively ($T = 300$ K, $\Gamma = 0.47$ meV, following the Kubo formalism).

At room temperature ($T = 300$ K), Fig. 2 shows the calculated surface conductivity of monolayer graphene with various chemical potentials (0–0.3 eV). The graphene chemical potential can be dynamically adjusted by means of the electrical voltage or chemical doping.

In our numerical calculations, the spectral response was performed by using full-wave electromagnetic software CST Microwave studio based on the Finite Element Method. The incident wave is transverse electromagnetic (TEM) wave and the polarization direction of the electric field is parallel to the y axis.

3. Results and discussion

To help understand the underlying mechanism of the GMTM, the passive EOT structure with an Si overlayer is compulsory to be discussed emphatically. The transmission spectrum of the DMD structrue sketched in Fig. 1(b) is shown in Fig. 3. To better illustrate the situation, another two partial structure cells are also considered, including a dielectric–metal–dielectric structure with hole array (DMD-H) and a dielectric–metal–dielectric structure with metallic pillar array (DMD-P), as sketched in the insets of Fig. 3. The simulation results of these structures with the same overlayers and substrates are also shown in Fig. 3. It is clear that the resonance peak f_2 induced by the DMD structrue is close to the resonance peak f_3 induced by the DMD-H structrue, which means the peak f_2 is mainly dominated by the DMD-H structure. On the contrary, the resonance peak f_1 of the DMD structrue could not correspond to any peaks of the DMD-H or DMD-P structures, which suggests the peak f_1 is related to both the DMD-H and DMD-P structures.