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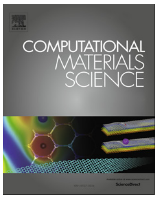

Tunable surface-plasmon-polariton-like modes based on graphene metamaterials in terahertz region

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ABSTRACT

Plasmonic response in graphene-based metamaterials show great potential for terahertz (THz) wave manipulation. In this work, we study the tunable surface-plasmon-polariton-like modes based on graphene complementary split ring resonators (CSRRs) in THz region. Our study suggests that these modes can be generated by graphene plasmonic metamaterials due to the diffraction coupling of surface plasmon and propagating electromagnetic (EM) wave. Furthermore, the modes can be tuned by stacking graphene plasmonic metamaterials layers or by changing the graphene Fermi level with electric field. Our results suggest graphene plasmonic metamaterials for both physical understanding and novel applications in THz region.

1. Introduction

Graphene, carbon atoms arranged in two dimensional honeycomb lattices, has attracted a lot of attention since its first practical production in 2004 [1]. This is mainly due to the reason that graphene has high carrier mobility [2], gate-controllable Fermi level, and broadband electromagnetic response [3], which is desirable for tunable, high-speed, and broadband optoelectronic devices. Recently, graphene has emerged as promising THz materials [3] for efficient THz wave manipulation with intrinsic plasmons, which could bridge 'THz' gap between microwave and far-infrared regions. As metamaterials afford efficient method to design and tailor nature materials, the alliance between graphene and metamaterials could further enhance optical processes of graphene. One of the promising designs is the hybridization of graphene and metamaterials, which could enhance plasmonic response for the development of THz and far-infrared detectors [4,5] and modulators [6,7]. Another method is to design metamaterials using graphene instead of noble metals in traditional metamaterials. Papasimakis et al. [8] compared single-layer graphene with single-layer of gold and proved that the magnetic response by highly doped graphene-based metamaterials is stronger than that by gold-based metamaterials. Fan et al. [9] found that the absorption in graphene can be enhanced by asymmetric split ring resonators (SRRs) in graphene-based metamaterials.

Plasmons in graphene play a pivotal role in the Dirac fermion dynamics, which have been probed by scattering-type scanning near-field optical microscope [10], and by other methods in THz and far-infrared regions [3,11]. Ju et al. [12] demonstrated light–plasmon coupling in graphene micro-ribbon array and suggested the resonant strength is quite large compared with the conventional two-dimensional electron gas in the room-temperature. Afterward, some other designs of graphene-based metamaterials such as graphene arrays [13], graphene rings [14], graphene nanodisks [15] appeared. However, these researches focused mainly on the localized surface plasmon (LSP), which can enhance the gross response of metamaterials by summing up independent localized effect. In metamaterials, the morphology of plasmonic structures could modulate the LSP and form the surface plasmon polaritons like (SPPs-like) modes, which can mimic the traditional surface plasmons [16]. In turn, these SPPs-like modes played an important role in the modulation and manipulation of electromagnetic waves for the optoelectronic devices.

In this work, we study the surface plasmon response of graphene plasmonic metamaterials based on complementary split ring resonators (CSRRs) in THz region. The plasmonic modes excited on the graphene metamaterials form the SPPs-like modes

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by diffraction coupling among the neighboring graphene CSRRs unit cells. We theoretically demonstrate that by the metamaterial interlayer coupling, the frequency of SPPs-like modes can shift by 14.17 THz and the resonant intensity enhance by 76% due to the strong Coulomb interaction among the adjacent graphene CSRRs layers. Furthermore, by tuning the Fermi level of graphene, the frequency of SPPs-like modes shift by 11.33 THz and the resonant intensity enhance by 41%. The graphene-based metamaterials exhibit great potential for tunable THz devices.

The sheet conductivity for single-layer graphene can be determined from the Kubo formalism [17,18]:

$$\sigma(\omega,\mu_c,\Gamma,T)=\frac{ie^2(\omega+i2\Gamma)}{\pi\hbar^2}\left[\frac{1}{(\omega+i2\Gamma)^2}\int_0^\infty E\left(\frac{\partial f_d(E)}{\partial E}-\frac{\partial f_d(-E)}{\partial E}\right)dE-\int_0^\infty\frac{\partial f_d(E)}{(\omega+i2\Gamma)^2-4(E/\hbar)^2}dE\right] \quad (1)$$

where ω is the circular frequency, μ_c is the Fermi level, E is the energy, Γ is the electron scattering rate, $\hbar$ is the reduced Plank's constant. And $f_d(\varepsilon)=(1+e^{(E-\mu_c)/K_bT})^{-1}$ is the Fermi–Dirac distribution, where e is the charge of an electron and T is temperature and K_b is Boltzmann's constant. The scattering rate Γ is proved to be independent of the Fermi level [19] (Γ^{-1} is the phenomenological electron relaxation time), which is given by $\Gamma=\mu\mu_c/eV_f^2$, and $V_f=1\times10^6$ m/s is the Fermi velocity, $\mu = 20{,}000\ \mathrm{cm}^2/\mathrm{V\,s}$ is the carrier mobility. Graphene can interact with light through intraband and interband electron transitions. In THz and far-infrared regions, the optical response is determined by intraband transition since the interband transitions are blocked. The first term in Eq. (1) is the intraband conductivity, while the second term is due to the interband contribution.

From the relationship of permittivity and conductivity, the complex permittivity of graphene can be expressed by [20]

$$\varepsilon = 1 + i\sigma/(\omega\varepsilon_0 t) \quad (2)$$

where $t = 0.34$ nm, is the thickness of a single-layer graphene and ε_0 is the permittivity of the vacuum. ε_r is the real part of the complex permittivity, and ε_i is the imaginary part.

We studied the plasmonic response in graphene metamaterials based on the single layer CSRRs as shown in Fig. 1a. The geometrical parameter of the structure are $a = 1$ μm, linewidth $w = 200$ nm, and the lattice spacing $c = 1.2$ μm. The graphene CSRRs is placed on a 17 nm thick quartz substrate with the permittivity 2.25. Graphene is described by a Kubo model with the Fermi level of 0.8 eV. CST MICROWAVE STUDIO was used to calculate the electromagnetic response with frequency domain solver. The simulation results shown in Fig. 1b refer to transmission spectra of the graphene plasmonic metamaterials excited by transverse electric (TE) incidence (black line) and transverse magnetic (TM) incidence (red line), respectively. The electric field is polarized along the y axis at TE incidence and along the x axis at TM incidence. TE incidence excites two plasmonic modes in 6.6 THz (r1) and 12.2 THz (r2) while another two plasmon modes in 15.9 THz (R1) and 18.8 THz (R2) are generated by TM incidence. To better understand the plasmonic resonance in graphene CSRRs, corresponding surface current are shown in Fig. 1c. It can be seen that at TE incidence, r1 has a circulating surface current which can be regarded as a magnetic plasmon mode, while r2 exhibit like a dipole mode. At TM incidence, the top and bottom polarized distribution inside the graphene CSRRs in R1 is in opposite direction and results in four directions of surface current. However, only one direction of surface current inside the graphene CSRRs has exhibited in R2, which is caused by the same orientation of the top and bottom polarization distribution. The surface current excited by TM incidence result in a quadrupole plasmon mode in R1 and a dipole plasmon mode in R2.

The dispersion of bulk plasmon can be expressed by $\omega^2 = {\omega_p}^2 + c^2k^2$, where ω is the wave frequency of EM wave, ω_p is the frequency of bulk plasma, c is the velocity of light in free space, and k is the wave vector of light [21]. In the presence of a planar boundary condition, a new mode, which is called surface plasmons (SPs), would emerge. Hybridization of plasmon with photon can form so-called surface plasmon polaritons (SPPs). There are mainly two cases that allow SPs to couple with light. One is the attenuated reflection using prism [22] and the other is periodic gating or surface roughness to provide a required momentum [23]. As such, metamaterials with periodic structures can support the coupling of light and plasmon to form SPPs-like modes due

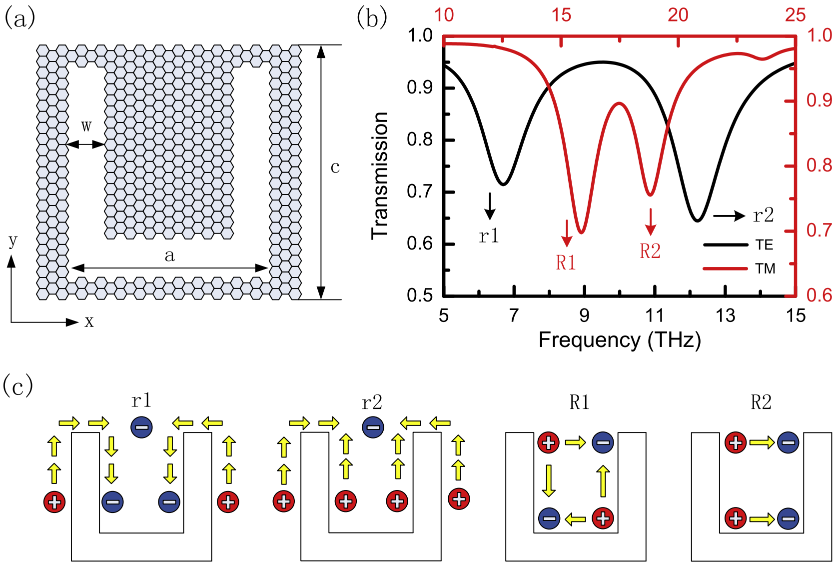

Fig. 1. (a) The 2D structure of single layer graphene CSRRs. (b) The transmission spectroscopy of single layer graphene CSRRs. The black curve including the plasmon modes of r1 and r2 refers to the simulation result at TE incidence. The red curve including the plasmon modes of R1 and R2 refers to the simulation result at TM incidence. (c) The corresponding surface current of all the plasmon modes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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