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Manipulating plasmonic waves transporting on graphene with graphene nanoribbon

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ABSTRACT

In this work, we simulate and analyze the influence of the short graphene nanoribbon on transporting of graphene plasmonic waves (GPWs) on an infinite graphene monolayer by a finite element method (FEM). We find that plasmonic waves transporting along one atomic-thick graphene are sensitive to short nanoribbons which are arranged near the infinite graphene sheet. There are two main different mechanisms for modulating GPWs transport on graphene sheet: One is that Fabry–Perot resonance of plasmonic waves on graphene nanoribbons, which function as the resonant line cavity; another is the formation of standing waves on the infinite graphene sheet based on GPWs reflecting at the end of graphene nanoribbon. Owing to tunability of the chemical potential μ_c of the doped graphene nanoribbon, we are also able to actively control plasmonic waves by gate voltage or chemical doping. The optical properties are also sensitive to the structural details of the system, namely width and distance modulation. It provides an additional handle to control plasmonic waves transferring and could find its application in designing infrared and THz plasmonic devices.

1. Introduction

Graphene Plasmonic Waves (GPWs) are surface plasmon waves traveling on one-atom-thick graphene, which have been experimentally proved recently [1,2]. Due to the unique band structures of graphene (conical-shaped conduction and valence bands meet at the Dirac point), GPWs are operated at far-infrared (FIR) and terahertz (THz) frequencies, which are more strongly confined and lower loss than surface plasmonic waves along the interface between metals and dielectric materials. More importantly, the complex surface conductivity of graphene is easily turnable by external electric field, magnetic field and gate voltage, which makes it popular in constructing active plasmonic devices. This paves the way to construct graphene plasmonic circuits. Until now, there are lots of researches on the optical properties of graphene [3,4] and its corresponding applications [10,5–8]. Single-layer graphene is used as a 2D platform for GPWs transporting [6,9,10]. Graphene ribbon is one of the most important nanocomponents [11–13] in designing plasmonic devices. Terahertz and infrared photodetectors based on graphene nanoribbon structures exhibit high responsivity and detectivity [14]. Individual and interacting graphene nanoribbons are proposed for graphene plasmon waveguiding [15,5]. The coupling GPW modes of double graphene layer have been specifically investigated [16]. Furthermore, Ref. [17] shows the plasmonic coupling in separated graphene sheets and demonstrates several plasmonic devices including splitter, switcher and modulator. However, there are few reports on plasmonic coupling between graphene and graphene nanoribbon. The idea is that the occurrence of a resonant process of GPWs in graphene nanoribbon is able to manipulate GPWs transferring on monolayer graphene. In this work, we develop a simple model formed by graphene–graphene nanoribbon for easily manipulating GPWs on graphene, given the interest in developing graphene plasmonic devices, such as filters or switchers.

2. Graphene conductivity and simulation methods

We simulate the transmission property of GPWs in a composite system consisting of an infinite graphene and a nanoribbon by a 2D finite element method (FEM) by using commercial software (Comsol Multiphysics). Fig. 1 shows the schematic diagram of the model. The graphene nanoribbon with width w is placed over the

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infinite graphene monolayer with a distance d. For simplicity, the whole structure is embedded in air. The TM polarized GPWs travel from the left port of the infinite graphene waveguide and out of the right port. We use the Kubo formula [10,18] for the complex surface conductivity of graphene, which is a function of the angular frequency ω (wavelength λ), chemical potential μ_c (also Fermi level E_F), temperature T and momentum relaxation time τ (inverse of the electron–phonon scattering rate). Within the random-phase approximation, the surface graphene conductivity $\sigma(\omega,\mu_c,T,\tau)$ can be simplified as a complex formulation consisting of interband and intraband contributions in the absence of an external magnetic field. The intraband term can be evaluated as

$$\sigma_{intra}(\omega,\mu_c,T,\tau) = -\frac{je^2k_BT}{\pi\hbar^2(\omega-j\tau^{-1})}\left[\frac{\mu_c}{k_BT}+2\ln(e^{\mu_c/k_BT}+1)\right] \quad (1)$$

and the interband term is approximated, for $k_BT \ll |\mu_c|$, $\hbar\omega$ by

$$\sigma_{inter}(\omega,\mu_c,T,\tau) = -\frac{je^2}{4\pi\hbar}\ln\left[\frac{2|\mu_c|-(\omega-j\tau^{-1})}{2|\mu_c|+(\omega-j\tau^{-1})}\right] \quad (2)$$

where $-e$ is the electron charge and $\hbar$ is the reduced Planck's constant. From Eqs. (1) and (2), it is found that, in the THz and far-infrared regions, the intraband contribution dominates, while the interband contribution becomes pronounced in the near-infrared and visible regions. Besides the fact that the parameter of temperature T is only exist in the intraband term indicates that the THz graphene plasmon is great sensitive to the temperature.

With respect to exciting surface plasmon in graphene, we set the chemical potential μ_c=0.15 eV and the momentum relaxation time τ=0.5 ps, which refers to Ref. [6]. The constant value of τ=0.5 ps is consistent with the ballistic transport features of graphene at room temperature (T=300 K) [20]. We choose the operating free-space wavelength of $\lambda = 10$ μm initially by which GPWs with both longer travel distance and higher confinement is excited [6]. Since graphene is one-atom-thick material with a thickness of 0.33 nm, which is the thinnest material existing in nature. In the implementation, for saving computing time and storage space, we define the graphene with a thickness of $\Delta = 1$ nm. We should point out that it is enough to validate our numerical simulations although other extremely small values for this thickness lead to similar results. Therefore, the corresponding volume conductivity of the bulk materia is σ/Δ. The equivalent permittivity of the Δ-thick graphene layer is given by $\epsilon_{g,eq} = 1+j\sigma\eta_0/(k_0\Delta)$, where $\eta_0(\approx 377\ \Omega)$ is the impedance of air, and $k_0 = 2\pi/\lambda$. We imbed the 2D-projection of our nanostructure of graphene–graphene nanoribbon into a square computational domain of 0.3 μm × 10 μm. Adaptive triangle meshing with a minimum feature resolution of 0.2 nm has been used in the simulations. Besides a perfectly matched layer (PML) for the truncation of open boundaries in our model, a convolutional-PML (CPML) method as an ideal candidate for evanescent wave is also adopted to absorb the GPWs at the end of the graphene monolayer.

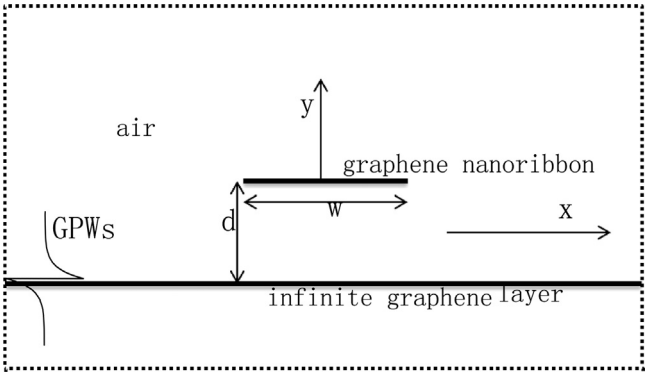

Fig. 1. Schematic diagram of the studying model and structure parameters.

3. Plasmonic wave coupling between graphene and graphene nanoribbon

As is well known, a single-layer graphene supports a plasmonic mode of anti-symmetric about the graphene plane. As a consequence of plasmonic coupling, two parallel graphene monolayers support two types of plasmonic mode: symmetric and anti-symmetric plasmonic modes, which originate from the odd and even superpositions of the anti-symmetric plasmonic mode in separate graphene sheets [17]. $\beta_{\mp}$ are the propagation constants of the anti-symmetric and symmetric modes which can be obtained from our simulation. Then, the coupling coefficient C_g and the coupling length L_c of plasmonic waves between the two graphene sheets can be figured out by [19]

$$C_g = |\beta_- - \beta_+|/2 \quad (3)$$

$$L_c = \pi/|\beta_- - \beta_+| \quad (4)$$

To show the GPWs coupling behaviors between two parallel graphene monolayers, the coupling coefficient C_g and the coupling length L_c versus different parameters are calculated, which are shown in Fig. 2. One can note that plasmonic coupling between two separated graphene sheets is directly related to the interlayer space d, incident wavelength λ and the chemical potential of graphene μ_c. Fig. 2(a) shows that the coupling coefficient exponentially decreases with the space d increases and approaches 0 at d=100 nm; while on the contrary shown in Fig. 2(b) and (c), the coupling coefficient grows logarithmically with the incident

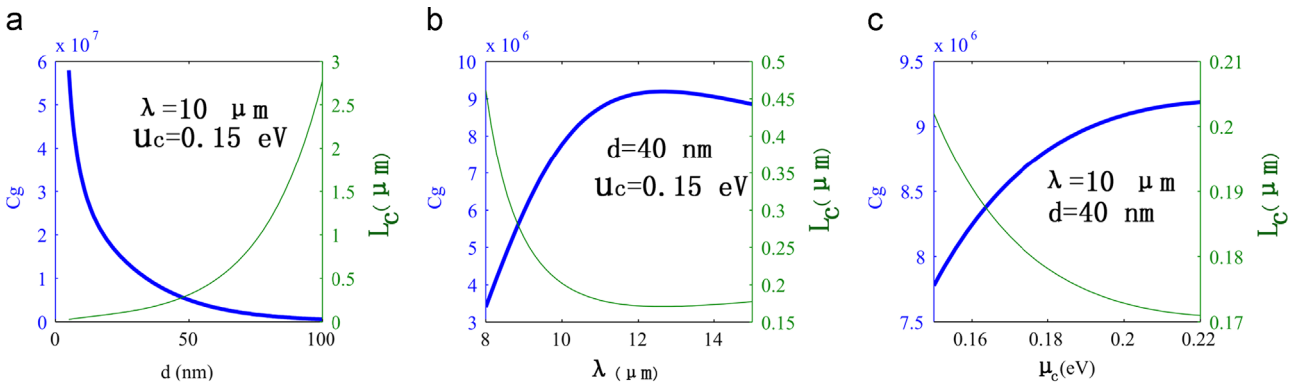

Fig. 2. The coupling coefficient C_g and the coupling length L_c of two septated graphene monolayers versus different parameters: (a) the distance d, (b) the incident wavelength λ, and (c) chemical potential μ_c with other parameters fixed.