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Plasmon switching effect based on graphene nanoribbon pair arrays

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ABSTRACT

We theoretically demonstrate the existence of plasmon switching effect in graphene nanostructure. By using finite-difference time-domain (FDTD) method, the plasmon resonance modes are studied in graphene nanoribbon pair arrays with the change of Fermi level, graphene width, and carrier mobility. It is found that the Fermi level and graphene width play an important role in changing the distribution of electric energy on different graphene nanoribbons, resulting in a significant plasmon switching effect. Moreover, we study the characteristic of resonance mode of one graphene ribbon by using glass rod with different shape. The effect of kerr material sandwiched between graphene nanoribbon pair is also considered.

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1. Introduction

Surface plasmon polaritons (SPPs) are an electromagnetic excitation which stems from a interaction between the atomic levels and charge density oscillations on a metal–dielectric interface [1,2]. Recently, it is found that SPPs have the ability of achieving optical switching effects and minimizing all-optical components [3–7]. Researchers have put many efforts into plasmonic analogs of optical switching in metal–dielectric nanocomposites and metal–insulator–metal (MIM) waveguides, indicating nonlinear and fast optical responses near the frequency of surface plasmon resonance [8–10]. Further, graphene has become extremely important plasmon materials due to its own unique properties such as local field enhancement, flexible tunability, exceptionally high mobility at room temperature, special band structure and observable plasmon shifts through chemically induced doping [11–15]. Thanks to these unique properties, plasmon-induced optical switching in graphene nanostructure is more easily tunable by changing the doping level of graphene via physical or geometric parameters than that in previous metallic structure [16–18].

All kinds of optical switches based on metallic nanostructures have been extensively investigated since the optical switching is vital to optical communication, networking, optical computation, and optical logic circuits [19–22]. For instance, several types of optical switching devices including nanoscale slots [23], asymmetric slits [24] and plasmonic waveguides [25] have been exploited as optical switches based on SPPs. Furthermore, the plasmonic optical switches are making profound changes to control light propagation due to localized surface plasmon resonance [26]. What is worth mentioning, in this paper, is that we propose a rather simple structure based on graphene nanoribbon (GNR) supporting plasmon switching effects in a nanoscale domain. Plasmon switching effects are also studied in many structures [27–29].

In this paper, the plasmon resonance effect in a planar graphene nanostructure is studied by employing finite-difference time-domain method (FDTD). It is found that the resonant GNR pair arrays support on-state and off-state at the same wavelength due to the localized plasmon resonance [30]. In contrast to the plasmon switching structures with monolayer graphene ribbon array [31], the plasmon resonance modes between the GNR pair can be controlled by altering the Fermi level and the graphene geometry parameter. Along with the Fermi level increasing or width decreasing, the resonance modes dramatically blue-shift. The on-state and off-state between the GNR pair at the same wavelength can be obtained from the distribution of electric energy. The carrier mobility of GNR has an effect on changing the depth of transmission. What's more, the hybrid structure composed of dielectric defect could provide a slight variation of resonant mode of the nearest graphene ribbon. And the optical bistability of kerr material sandwiched between graphene nanoribbon pair arrays is also studied.

2. Design of structure model

The optical feature of graphene can be characterized by the surface conductivity σ composed of the intraband part and the

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interband part, which can be expressed as $\sigma = \sigma_{\text{int ra}} + \sigma_{\text{int er}}$. The intraband electron–photon scattering, i.e. $\sigma_{\text{int ra}}$, can be described as [32,33]:

$$\sigma_{\text{int ra}}(\omega) = \frac{2e^2T}{\pi\hbar}\frac{i}{\omega + i\tau^{-1}}\ \log\left[2\ \cosh\left(\frac{E_f}{2K_BT}\right)\right] \tag{1}$$

Also, the interband transition contribution, i.e. $\sigma_{\text{int er}}$, may be approximately written as

$$\sigma_{\text{int er}}(\omega) = \frac{e^2}{4\hbar}\left[H\left(\frac{\omega}{2}\right) + \frac{4i\omega}{\pi}\int_0^{\infty}\frac{H(\varepsilon) - H(\omega/2)}{\omega^2 - 4\varepsilon^2}d\varepsilon\right] \tag{2}$$

Here e and $\hbar$ are the elementary charge and reduced Plank constant, respectively. ω is the angular frequency of the electromagnetic wave, $E_f = \hbar v_f(\pi n)^{1/2}$ is the Fermi energy, where n is the carrier density and $v_f = 10^6$ m/s is the Fermi velocity in graphene, $\tau = \mu E_f/ev_f^2$ is the relaxation time, $T = 300$ K is the room temperature, and K_B is the Boltzmann constant. From Eq. (1), it is observed that the propagation characteristics of the graphene plasmons can be efficiently controlled by changing the Fermi energy E_f. The main consideration in this article is the intraband transmission characteristics of graphene. At room temperature, $K_BT \approx 0.026$ eV, from the Eq. (1), the intraband conductivity $\sigma_{\text{int ra}}$ of graphene, similar to Drude model, can be further simplified as

$$\sigma_{\text{int ra}} = i\frac{e^2E_f}{\pi\hbar^2(\omega + i\tau^{-1})} \tag{3}$$

Fig. 1(a) schematically shows the graphene plasmon structure, which is composed of the periodic arrays of GNR pair (marked with i and ii) along y direction under investigation. The length of GNR pair along the x direction is infinite. The periodic arrays of GNR pair are located at the upper and lower surfaces of dielectric material, respectively. For simplicity, we assume that dielectric material is air. And the periodic arrays of GNR pair are suspended in air. The incident plane wave with E_y polarization propagates along the z axis direction. In our calculations, the perfectly matched layer (PML) boundary conditions are used at the above and bottom of the simulation unit (z axis direction) while bloch periodic boundary conditions are employed in both the boundary along y axis direction.

The period of the structure along y direction is P=400 nm. Here the upper GNR and the lower GNR are defined as graphene i and graphene ii in the whole paper. The thickness of each graphene nanoribbon is fixed as 0.5 nm. The width of the upper and lower nanoribbon is $W^i = W^{ii} = 200$ nm. The Fermi energy of each nanoribbon is set as $E_f^i = E_f^{ii} = 0.6$ eV, where the E_f^i and E_f^{ii} denote the Fermi energy of the upper and lower graphene nanoribbon, respectively. The gap distance between the GNR pair is d=200 nm, and the carrier mobility μ of GNR is taken as μ=10,000 cm^2/(V s). Fig. 1(b) indicates the transmission spectra of the system for $E_f^i = E_f^{ii}$ and $W^i = W^{ii}$, and one can see that there is only one transmission dip.

Employing the temporal coupled mode theory [24], the transmission T of the system can be estimated with the following equation:

$$T = \frac{(\omega - \omega_0)^2 + (1/\tau_i)^2}{(\omega - \omega_0)^2 + (1/\tau_i + 1/\tau_\omega)^2} \tag{4}$$

where ω and ω_0 represent the frequency of incident light and the resonance frequency, respectively. $1/\tau_i$ is the decay rate of the field on account of the internal loss in the two GNRs, and $1/\tau_\omega$ is the decay rate due to the power escape through the waveguide. From the Eq. (3) we can know that there is a transmission dip with value of $(1/\tau_i)^2/(1/\tau_i + 1/\tau_\omega)^2$ at the resonant frequency ω_0. The normal-incidence wave excites the plasmonic wave in the system when propagating in each GNR, the resonant frequency ω_0 in each graphene ribbon can be further approximated as

$$\omega_0 = \sqrt{\frac{2e^2 \times E_f}{\hbar^2\varepsilon_0(\varepsilon_{r1} + \varepsilon_{r2})W}} \tag{5}$$

in which W is the width of the GNR, ε_{r1} and ε_{r2} are the effective dielectric constants of the materials the above and below GNR, respectively. Here, ε_{r1} and ε_{r2} are both assumed to be 1.0. From Eq. (5), we can note that the plasmon resonance mode in graphene nanoribbon i or graphene nanoribbon ii is tunable by changing the Fermi energy E_f^i or E_f^{ii}, width W^i or W^{ii}, ε_{r1} and ε_{r2}. The hybrid structure can pave an interesting way toward potential applications in graphene plasmon.

3. Results and discussions

In order to understand the key to affect the plasmon resonance feature in our scheme, the GNR pair marked with graphene i and graphene ii are set as different Fermi levels E_f^i and E_f^{ii}. The transmission characteristics of two arrays of GNR pair are investigated firstly. The relative parameters are assumed as $W^i = W^{ii} = 200$ nm, d=200 nm and μ=10,000 cm^2/(V s). We set $E_f^{ii} = 0.6$ eV unchanged, which means that the resonant wavelength of the below graphene ribbon remains almost unchanged, the evolution of transmission spectra as the altering of E_f^i is shown in Fig. 2(a).

It can be seen that there are two plasmon resonance modes with different wavelength $\lambda_1 = 6.254$ μm and $\lambda_2 = 7.278$ μm when $E_f^i = 0.8$ eV ($E_f^i > E_f^{ii}$). When $E_f^i = 0.6$ eV ($E_f^i = E_f^{ii}$), there is only one plasmon resonance mode at wavelength $\lambda_2 = 7.273$ μm. When $E_f^i = 0.4$ eV ($E_f^i < E_f^{ii}$), as we expect, there are also two transmission dips corresponding to wavelengths of $\lambda_4 = 7.273$ μm and $\lambda_5 = 8.916$ μm, which represent two different resonance modes correspond to graphene ribbon i and ii. What's more, the plasmon resonance modes in graphene ribbon i have a blue-shift as the E_f^i

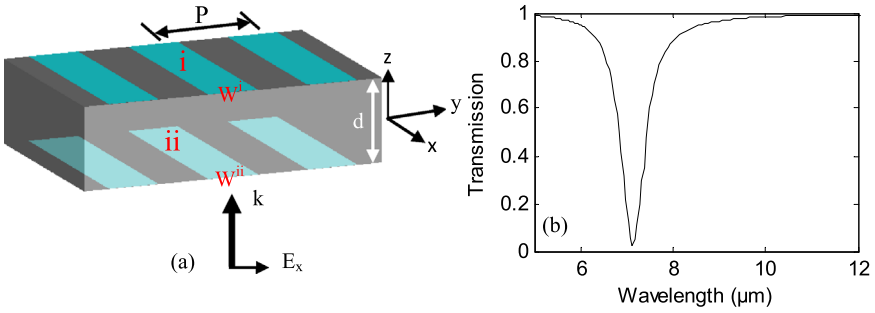

Fig. 1. (a) Three cells along y direction of the graphene nanostructure. (b) The transmission spectra of the graphene configuration under study.

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