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Tunable plasmon induced transparency based on bright–bright mode coupling graphene metamaterial

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ABSTRACT

A graphene-based metamaterial structure with tunable plasmon induced transparency (PIT) effect is numerically and theoretically researched in this paper. Both the collinear and parallel graphene strips serve as bright mode and a PIT window emerges due to the weak hybridization between them. The transparency window can be tuned by not only adjusting the geometry parameter of the structure but also changing the chemical potential of the graphene strips. Different from the reported tunable PIT system, the spectra width and resonance strength can be tuned with the PIT peak at a fixed frequency in this research. Moreover, the Q factor can be affected by the distance between two bright modes and a figure of merit (FOM) as high as 15.20 can be achieved in this research. These properties expand the application for PIT phenomenon in mid-infrared metamaterial devices, such as filter, modulator and sensor.

1. Introduction

Electromagnetically induced transparency (EIT), as a very important phenomenon in quantum physics, was firstly observed in atomic regime and realized in a three-level system, which leads to a sharp transparency window within a broad absorption spectrum because of the quantum destructive interference of the two excitation pathways from ground state to the upper level [1]. Although this intriguing effect exhibits tremendous potential application because of its violent resonance and sharp dispersion, the investigation and development in EIT effect is severely constrained in practical application for the specific and harsh terms, such as coherent pumping, high intensities and cool temperature [2]. To solve this problem, many researchers take effort to mimic the classical EIT effect in a new way and the plasmon induced transparency (PIT) effect based on metamaterial is a promising substitute because of its no pumping allowed, room temperature, flexible design and easy implementation. For example, Zhang et al. firstly proposed a metamaterial structure to realize the PIT effect in theory by the near-field coupling between silver optical antennae [3]. Then, Liu et al. experimentally demonstrated the PIT effect based on the complementary metamaterial consisting of cut-out structures in a thin gold film [4]. Up to now, PIT has attracted enormous attentions due to its all kinds of potentially important application in the field of sensors [4–7], modulators [8,9], optical switches [10,11], polarization converters [12,13] and so on.

Generally speaking, there are two kinds of schemes to realize PIT: the bright–dark mode coupling (direct coupling) [3,4,14–16] and the bright–bright mode coupling (indirect coupling) [7,17–20]. Different from the first method based on the destructive interference between bright mode and dark mode, the second one originates from the detuning between two bright modes, which has attracted the attention of more and more researchers. A highly-dispersive PIT spectra response can be obtained in the bright–bright mode coupling metamaterial consisting of two sliver strips [17]. And tunable PIT phenomenon based on bright–bright mode coupling graphene metamaterial is realized in terahertz frequency [18,20]. Then the bright–bright mode coupling PIT is used in refractive index sensor with a figure of merit (FOM) as high as 12 [7]. Recently, the PIT in two-bright mode coupling system is described by introducing a radiating two-oscillator (RTO) model which has been confirmed experimentally [19,21]. Although the line width and resonant strength are tuned by geometry parameter of the structure in these researches, it is inconvenient once the device is fabricated and there is an obvious defect in this method that the PIT peak will shift with the adjusting of structure, which hamper the practical application in filter and modulator for two-bright mode coupling PIT

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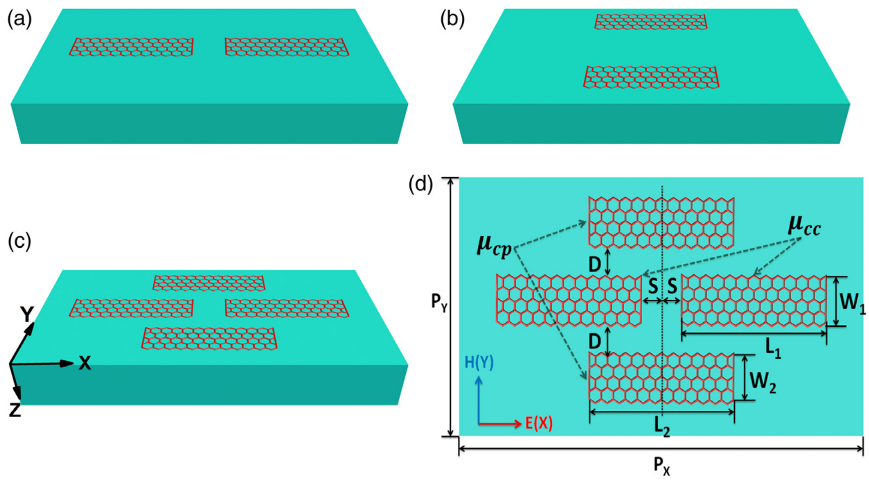

Fig. 1. (a) The unit cell with the standalone collinear graphene strips. (b) The unit cell with the standalone parallel graphene strips. (c) The unit cell of the composite graphene metamaterial structure. (d) The top view of the unit cell for the composite graphene metamaterial structure with geometrical parameters.

effect. Moreover, the peak frequency of the transmission window can be tuned by changing the chemical potential of graphene easily, but the tunability of bandwidth and resonant strength is often necessary in practice, which has not been discussed in the reported bright–bright mode coupling PIT system based on graphene metamaterial [7,18,20].

In this article, we numerically and theoretically study the PIT effect based on bright–bright mode coupling graphene metamaterial structure consisting of two collinear graphene strips and two parallel graphene strips. The PIT window can be controlled by adjusting the geometric parameters and the frequency of the PIT peak can be dynamically tuned over a broad frequency when the chemical potential of graphene is varied. Importantly, the most obvious advantage in this research is that we can manipulate the line width and resonant strength with the PIT peak located at a fixed frequency by adjusting the chemical potential of the collinear and parallel graphene strips to different valves. Besides, it can be found that the distance between two bright modes can affect the Q factor which is closely related to the performance of a refractive index sensor.

2. Metamaterial structure and FDTD simulation model

As shown in Fig. 1, the metamaterial structure to demonstrate the PIT phenomenon consists of two collinear graphene strips and two parallel graphene strips on the substrate (refractive index $n_s = 1.4$ and thickness $d = 50$ nm) while the chemical potential of the collinear and parallel graphene strips are μ_{cc} and μ_{cp}, respectively. Both the collinear and parallel graphene strips serve as bright mode in our research. The incident plane light is along the z-direction with the polarization along the x-direction. The presented graphene metamaterial is a periodical structure with the period $P_x = 350$ nm in x-direction and $P_y = 200$ nm in y-direction. Hence periodic boundary conditions are applied along x-direction and y-direction while perfect match layers (PML) are along z-direction, and Finite-difference time-domain (FDTD) method is adopted in the simulation. The length and width of the collinear strips is $L_1 = 110$ nm and $W_1 = 30$ nm while the length and width of the parallel strips is $L_2 = 120$ nm and $W_2 = 30$ nm. And the lateral displacement and distance between the collinear strips and parallel strips is $S = 15$ nm and $D = 40$ nm, respectively. In this research, the surface conductivity σ for a single layer of graphene can be given by the well-known Kubo formalism [22]:

$$\sigma\left(\omega,\ \Gamma,\mu_c,T\right)=\sigma_{intra}\left(\omega,\Gamma,\mu_c,T\right)+\sigma_{inter}\left(\omega,\Gamma,\mu_c,T\right) \tag{1}$$

$$\sigma_{intra}\left(\omega,\ \Gamma,\mu_c,T\right)=\frac{-ie^2}{\pi\hbar^2(\omega+i2\Gamma)}\int_0^{\infty}\xi\left(\frac{\partial f_d\left(\xi\right)}{\partial\xi}-\frac{\partial f_d\left(-\xi\right)}{\partial\xi}\right)d\xi \tag{2}$$

$$\sigma_{inter}\left(\omega,\Gamma,\mu_c,T\right)=\frac{ie^2\left(\omega+i2\Gamma\right)}{\pi\hbar^2}\int_0^{\infty}\frac{f_d\left(-\xi\right)-f_d\left(\xi\right)}{(\omega+i2\Gamma)^2-4(\xi/\hbar)^2}d\xi \tag{3}$$

$$f_d\left(\xi\right)\equiv\frac{1}{\exp(\left(\xi-\mu_c\right)/(k_BT))+1}. \tag{4}$$

The two conductivity terms in formula (2) and (3) are referred as the intraband and interband terms, respectively. And the formula (4) is the Femi–Dirac distribution. Where ω is the angular frequency, e is the charge of an electron, μ_c is the chemical potential or Fermi energy of the single layer graphene, $\hbar = h/2\pi$ is the reduced Planck's constant and k_B is the Boltzmann's constant. The scattering rate $\Gamma = 0.00051423$ eV and environment temperature $T = 300$ K are the default values in the simulating software and taken into account in this research. From the reference [23], we can know that the carrier mobility μ of graphene film ranges from ~1000 cm^2/(V s) to 230 000 cm^2/(V s) and the Fermi velocity v_f in graphene is 10^6 m/s, so the corresponding scattering rate ranges from 0.0000174 to 0.0056742 eV which can be calculated by the relations $\Gamma = \hbar/(2\tau)$ and $\tau^{-1} = ev_f^2/(\mu\mu_c)$ [24], where τ is the relaxation time and the chemical potential μ_c changes from 0.58 eV to 0.82 eV in our research. Apparently, the scattering rate $\Gamma = 0.0051423$ eV in our research falls within the reasonable range.

3. The radiating two-oscillators model for bright–bright mode coupling system

The bright–bright mode coupling in the metamaterial structure can be explained by a radiating two-oscillator (RTO) model [19,21]:

$$\ddot{p_1}\left(t\right)+\gamma_1\dot{p_1}(t)+\omega_1^2p_1\left(t\right)-\Omega^2\exp\left(i\varphi\right)p_2\left(t\right)=f_1(t) \tag{5}$$

$$\ddot{p_2}\left(t\right)+\gamma_2\dot{p_2}(t)+\omega_2^2p_2\left(t\right)-\Omega^2\exp\left(i\varphi\right)p_1\left(t\right)=f_2(t) \tag{6}$$

where ω_1, ω_2 is the resonance frequency of the radiative resonators $p_1(t)$ and $p_2(t)$, respectively. And γ_1, γ_2 is the damping factor of the two radiative resonators. $\Omega^2\exp(i\varphi)$ is a complex coupling coefficient and φ is the phase shift between two oscillators. Because the two bright mode are exposed to the same optical field, the external force $f_1\left(t\right) = f_2(t)$ and $\varphi = 0$. By assuming $p_1\left(t\right) = P_1\exp(-i\omega t)$ and $p_2\left(t\right) = P_2\exp(-i\omega t)$ as