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Tunable plasmon-induced transparency with graphene-based T-shaped array metasurfaces

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ABSTRACT

The frequency tunable Plasmonic induced transparency (PIT) effect is researched with a periodically patterned T-shaped graphene array in mid-infrared region. We adjust the geometrical parameters to obtain the optimized combination for the realization of the PIT response and use the coupled Lorentz oscillator model to analysis the physical mechanism. Due to the properties of graphene, the PIT effect can be easily and markedly enhanced with the increase of chemical potential and carrier mobility. The frequency of PIT effect is also insensitive with the angle of incident light. In addition, we also propose the π shaped structure to realizing the double-peak PIT effect. The results offer a flexible approach for the development of tunable graphene-based photonic devices.

1. Introduction

Graphene is a two-dimensional (2D) conductive material which arranged by a planar sheet of carbon atoms [1]. It has attracted tremendous interest due to its unique tunability, special optical characteristics, high degree of electromagnetic confinement and presumably long plasmon lifetime [2–5]. Since it was produced in 2004, the great potential of it in academia and industry lead to a widely investigated. The plasmonic devices of graphene metasurfaces have attracted worldwide interest currently and are mainly researched with the incorporation of tunable and nonlinear [6–14]. Metasurfaces are the one- and two-dimensional artificial composite structures with sub-wavelength periodicity and have exotic electromagnetic properties [15–18]. In 2012 years, Arya Fallahi and Julien Perruisseau-Carrier proposed the biperiodic graphene metasurfaces and researched the tunability of graphene theoretically [19]. In 2015 years, Miao et al. researched the widely tunable terahertz phase modulation with gate-controlled graphene metasurfaces [20].

Electromagnetically induced transparency (EIT) is an optical nonlinear phenomenon based on quantum interference effect that can enhance light transmission over a narrow spectral region [21,22]. Plasmonic induced transparency (PIT) is the novel phenomenon analogous to EIT, also is the special case of Fano resonance. In general, there are two common approaches to realizing PIT response: the direct destructive interference between bright-dark mode coupling [23,24] and the detuning of two bright modes [25,26]. In recent years, PIT in metasurfaces has been proposed in variety of structures, especially the graphene based metasurfaces [27–32]. Shi et al. proposed the π shaped graphene nanostructures and reveal the mechanism of EIT-like response in graphene structures use the coupled radiative and dark elements model, demonstrated that the EIT in graphene is closer to EIT in atomic system then which in metal structures [33]. Liu et al. have researched the dynamic modulation of PIT in graphene-based metamolecules with external magnetic field [34]. Compare to these researches, we have a systematic simulation on the proposed structure and analysis it with theory model.

In this work, a simple structure with PIT response is presented and followed by a numerical study. In the proposed system, the physical mechanism of PIT phenomenon can be explained with the coupled Lorentz oscillator model. By adjusting the geometrical parameters, the off-to-on response of PIT and the optimized design can be achieved. The PIT response would be also significant tuned by the varying μ_c and μ of graphene. In addition, the π shaped graphene strips structure are proposed to realize the double PIT peaks. This work provides potential ways for realizing the controlling of light in nanophotonic devices.

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2. Theoretical and model

The schematics of the designed graphene-based three-dimension PIT metasurfaces are presented in Fig. 1. The proposed graphene structures can be made by the Hydrogen Etching method for Chemical Vapor Deposited (CVD) monolayer graphene and then transferred to a silicon dioxide wafer [35–40]. As shown in Fig. 1(b), the structure is composed of periodically patterned T shaped graphene nanostrips adheres to a substrate which refractive index is considered to be 1.5. Each T shaped graphene strip consists of two nanostrips which are shown in Fig. 1(a). The gray one strip in Fig. 1(a) is used to show the moving process of strip 2 from Fig. 1(b). The period of the unit cell is P in both x and y directions. The thickness of substrate is denoted by a. We found that when the thickness a set from 60 nm to 120 nm, there are almost not effects of thickness on the transmission spectra. So that in our simulation, the substrate thickness is fixed at 60 nm. The strip 1 and strip 2 are designed as length L with width W and length l with width w, respectively. The separation of two strips is denoted as t, and the lateral migration of strip 2 is denoted as s which is considered as the structural asymmetry factor. The system is illuminated by the plane wave from z direction with the incident angle θ, and its electric component is parallel to x axis means the TE polarization. In this structure, the thickness of graphene is ignored, and the surface conductivity σ is computed by Kubo formula including interband and intraband transition [41]. In mid-infrared region, when $\mu_c \gg k_B T_m$, the intraband contribution dominates and the surface conductivity can be simplified as [9]:

$$\sigma(\omega) = \frac{e^2 \mu_c}{\pi \hbar^2} \frac{i}{\omega + i/\tau}, \tag{1}$$

where $e, \hbar$ and k_B are the universal constants representing the electron charge, Boltzmann's constant and reduced Planck's constant, respectively. ω is the photon frequency. μ_c, τ and T_m are the chemical potential, relaxation time and temperature, respectively. And the relaxation time τ can be expressed by $\tau = (\mu\mu_c)/(eV_f^2)$. Here, $V_f = 1 \times 10^6$ m/s is the Fermi velocity and μ is the electron mobility. In this work, the room temperature is assumed to be 300 K. The chemical potential and electron mobility are set to 0.5 eV and 20,000 $\mathrm{cm^2\ V^{-1}\ s^{-1}}$ initially. Due to the tunability of graphene, the resonance frequency ω_r can be controlled by the chemical potential. Here the wave vector of surface plasmon along the graphene nanostrip can be expressed as $k_{spp} = \hbar\omega_r^2/(2\alpha_0\mu_c c)$ [42], which also satisfies $k_{spp} \propto 1/L_G$. Where $\alpha_0 = e^2/(\hbar c)$ is the fine structure constant, L_G is the length of graphene nanostrip and c is the velocity of light in vacuum.

The three-level plasmonic system is adapted to explain the physical mechanism of the wavelength tunable PIT response between two graphene strips in the unit cell. The incident electromagnetic field is denoted as $\widetilde{E}_0 e^{i\omega t}$. The bright mode and dark mode in the PIT system can be expressed as $|D\rangle = \widetilde{D}(\omega)e^{i\omega t}$ and $|Q\rangle = \widetilde{Q}(\omega)e^{i\omega t}$. The resonance frequencies and the damping factors of the bright mode and the dark mode are ω_D, ω_Q and γ_D, γ_Q, respectively. According to the coupled Lorentz oscillator model [43–45], the field amplitudes are obtained in:

$$\begin{pmatrix} \omega - \omega_D + i\gamma_D & \kappa \\ \kappa & \omega - \omega_Q + i\gamma_Q \end{pmatrix} \begin{pmatrix} \widetilde{D} \\ \widetilde{Q} \end{pmatrix} = \begin{pmatrix} g\widetilde{E}_0 \\ 0 \end{pmatrix}. \tag{2}$$

Here, g is the geometrical parameter expressing the coupling strength of the bright mode with the incident field and κ is the coupling coefficient between bright and dark modes. The complex amplitude of the bright mode can be derived as:

$$\widetilde{D} = \frac{-g\widetilde{E}_0(\omega - \omega_Q + i\gamma_Q)}{(\omega - \omega_D + i\gamma_D)(\omega - \omega_Q + i\gamma_Q) - \kappa^2}. \tag{3}$$

Thus, the transmission of the metasurfaces PIT device can be deduced as:

$$T(\omega) = 1 - \left| \frac{\widetilde{D}}{\widetilde{E}_0} \right|^2. \tag{4}$$

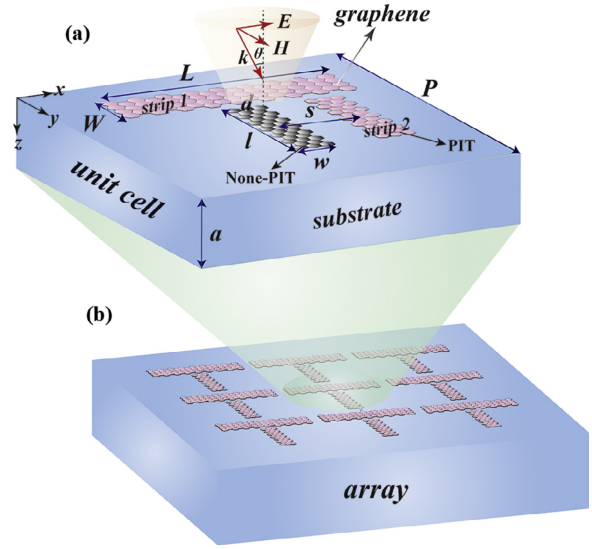

Fig. 1. (a) 3D schematic illustration of the unit cell of the periodically patterned T shaped graphene nanostrips. (b) Schematic of the graphene metasurfaces array.

As shown in Fig. 2, the optimized geometric parameters are chosen as P = 250 nm, L = 140 nm, W = 50 nm, l = 120 nm, w = 30 nm, d = 10 nm and s = 40 nm, respectively. Under the normal incident light, with above settings, the bright-dark PIT system can be realized obviously in Fig. 2(a) in the light green line with triangle. By contrast, the transmission spectra with only one strip are calculated separately and shown in Fig. 2(a). The resonance of incident light and strip 1 (act as bright mode) leads to the transmission dip in the spectrum with pale blue line and rectangle symbol, while the strip 2 act as the dark mode so there is none-resonance with incident light, the transmission spectrum almost a flat line in dark green with circle symbol in Fig. 2(a). The electric field distributions at 20.25 THz (the points "b" and "c" in Fig. 2(a)) are gathering around the edge of the graphene strip, which are shown in Fig. 2(b)–(c). It can be found that both two strips have energy coupling, but the resonant modes of strip 1 and strip 2 are in different frequency range. The simulations show the resonance frequency of strip 1 is 20.25 THz, which can be regarded as bright mode. The resonance frequency of strip 2 is greater than 50 THz which is out of the investigate frequency domain, therefore it can be seen as a dark mode. Fig. 2(d)–(f) show the electric field distributions corresponding to the points "d", "e" and "f" that labeled in Fig. 2(a). In Fig. 2(d) and (f), the electric modes in strip 2 are obtained the y-axis distribution with the effect of the resonance in strip 1. The answer to the question of the origin of the PIT is illustrated in Fig. 2(e). The field energy in strip 1 is weak due to the destructive interference of the coupling between two excitation ways: strip 1 with incident field, and strip 1 with strip 2. The comparison of simulation and theory is shown in Fig. 3. The parameters are chosen as P = 250 nm, L = 140 nm, W = 50 nm, l = 120 nm, w = 30 nm, d = 10 nm and s = 40 nm. The coupled Lorentz oscillator model can be fitted well with the simulation result with $\omega_Q = \omega_D$ = 20.25 THz, γ_Q = 0.01, γ_D = 0.233, g = 0.17 and κ = 0.835. Here we add a loss factor with value of 0.04 in the theoretical transmittance for the substrate of structure.

3. Results and discussion

The three-dimension simulations are calculated by COMSOL Multiphysics based on finite element method. In our simulation, the graphene is considered as a planar and modeled by using the surface current boundary condition, the x and y directions are applied the periodic