Tunable electromagnetically induced transparency at terahertz frequencies in coupled graphene metamaterial*

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A graphene-based metamaterial with tunable electromagnetically induced transparency (EIT)-like transmission is numerically studied in this paper. The proposed structure consists of a graphene layer composed of coupled cut-wire pairs printed on a substrate. The simulation confirms that an EIT-like transparency window can be observed due to indirect coupling in a terahertz frequency range. More importantly, the peak frequency of the transmission window can be dynamically controlled over a broad frequency range by varying the Fermi energy levels of the graphene layer through controlling the electrostatic gating. The proposed metamaterial structure offers an additional opportunity to design novel applications such as switches or modulators.

Keywords: graphene, metamaterial, electromagnetically induced transparency

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1. Introduction

Electromagnetically induced transparency (EIT) in atomic physics is a very important phenomenon, which is the result of a quantum destructive interference between two pathways induced by another field.[1] EIT has many potential applications, such as ultraslow light propagation, optical data storage, sensors, and optical switching.[2] However, due to the specific experimental conditions, the practical application of EIT in an atomic system has been restricted. Recently, much interest of researchers focused on the mimic classical EIT phenomenon by using metamaterial at microwave,[3] terahertz,[4] and optical frequency.[5] Many structures have been proposed and demonstrated to realize EIT-like components, such as dipole antennas,[6] split ring resonators,[7] detuned electric dipoles,[8] array of metallic nanoparticles,[9] and waveguide-coupled resonators.[10] These investigations have promoted the development of EIT behavior.

Up to now, the research of EIT in metamaterial has focused on two main approaches: the bright-bright mode coupling (indirect coupling)[11] and the bright-dark mode coupling (direct coupling).[12–18] Aydin *et al.* demonstrated narrow transmission resonances at near-infrared wavelengths by utilizing coupled asymmetric split-ring resonators.[7] A resonance with an anti-symmetric current configuration can be activated so that these currents radiated fields will interfere destructively. Therefore, the incident wave propagates, accompanied with loss in a narrow frequency range. Duan *et al.* proposed the polarization-insensitive and wide-angle plasmonically induced transparency by planar metamaterial.[19,20] Jin *et al.* theoretically investigated the plasmonic EIT-like spectral response at optical frequencies by using a planar metamaterial which consists of two silver strips.[11] EIT with large group index induced by simultaneously exciting the electric and the magnetic resonance has been numerically and experimentally demonstrated by Li *et al.*[13]

However, the transparency windows of most work mentioned above have been realized at a fixed frequency. It is essential to reconstruct the geometries or modify the substrates if the resonance is tuned to different working frequencies, but it is difficult to achieve once the devices are fabricated. Obviously, how to obtain a tunable EIT has been the focus of interest to the researchers recently. Nakanishi *et al.*[21] studied a method of dynamically controlling the properties of EIT by using varactor diodes to manipulate the structural symmetry of the metamaterial. The transparent window and the corresponding slow light effect of semiconductor-based EIT proposed by Bai *et al.*[22] can be continuously tuned in a broad frequency regime, owing to the fact that the carrier concentration of semiconductor can be actively changed by varying

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temperature. However, it is inconvenient to introduce varactor diodes into the structure if the transparency window is realized in terahertz or optical frequencies and changing the temperature is infeasible in many cases.

Graphene, which is a two-dimensional layer of carbon atoms arranged in a honeycomb pattern, has become a hot material in researches since it was discovered in 2004.[23–28] Its conductivity can be controlled by changing the Fermi energy levels. The Fermi energy can be tuned from -1 to 1 eV by chemical doping or electrostatic gating. Cheng *et al.* investigated the Mid-infrared tunable optical polarization converter consisting of asymmetric graphene structure.[29,30] Ding *et al.* studied the single and multiple transparency windows originating from the quantum effect of Autler–Townes splitting.[31] Amin *et al.* proposed a novel electrically tunable hybrid graphene-gold Fano resonator which can be regarded as direct coupling.[32] In this work, the graphene was introduced into the EIT metamaterial with indirect coupling. Therefore, the transparency windows for the structures with indirect coupling could be dynamically controlled over a broad frequency range by varying the Fermi energy levels of the graphene layer (through electrostatic gating).[33,34] It is very convenient to tune the properties of the EIT compared with those of other work mentioned above. The EIT-like phenomenon can be observed in terahertz frequency. The proposed graphene-based tunable EIT has some important potential practical applications.

The rest of the present paper is described as follows. In Section 2, the structure of the graphene-based EIT is studied. Then, we briefly review the electrodynamics of the graphene. In Section 3, we present the numerical results and discussion. Finally, the concluding remarks are given in Section 4.

2. Schematic of the metamaterial and theoretical model

The unit cell of the graphene-based EIT metamaterial we propose is shown in Fig. 1. The resonator is printed on a dielectric substrate. The graphene layer and the substrate are illustrated in grey and green, respectively. Two kinds of cut-wire resonators with different resonant frequencies are separated with a gap of g_2. The resonant frequencies of different cut-wire resonators are determined by the length of each graphene wire s_1, and the gap of g_1 in the cut-wire. The difference between the two resonant frequencies will be determined by the difference between w_1 and w_2. The thickness values of graphene and substrate are d_1 and d_2 respectively. The array periodicities in both x and y directions are both l. The relative permittivity of the substrate is denoted as $\varepsilon_{\rm d}$. The wave vector $\boldsymbol{K}(\omega)$ for incident wave is perpendicular to the xy plane.

The surface conductivity σ of graphene is the sum of the intraband $\sigma_{\rm intra}$ and the interband term $\sigma_{\rm inter}$. The intraband term can be expressed as[35,36]

$$\sigma_{\rm intra}(\omega) = {\rm i}\frac{e^2 k_{\rm B} T}{\pi\hbar^2(\omega+{\rm i}\Gamma)}\left(\frac{E_{\rm F}}{k_{\rm B}T}+2\ln({\rm e}^{-E_{\rm F}/k_{\rm B}T}+1)\right), \quad (1)$$

where e is the charge of the electron, $k_{\rm B}$ is the Boltzmann constant, T is the temperature in K, $\hbar = h/2\pi$ is the reduced Planck constant, $\Gamma = 1/\tau$ is the carrier scattering rate with τ being the carrier relaxation time, and $E_{\rm F}$ is the Fermi energy in graphene.

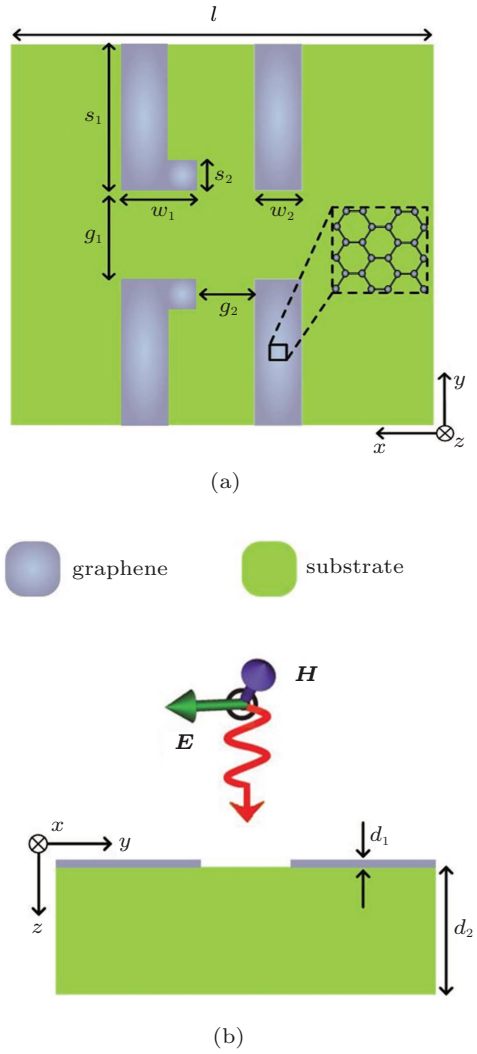


Fig. 1. (color online) (a) Top view of the unit cell with dimensions. (b) Cross-section view and the normally incident excitation.

The interband term of the graphene conductivity for $k_{\rm B}T << |\hbar\omega - 2E_{\rm F}|$ reads[26,35,36]

$$\sigma_{\rm inter}(\omega) = {\rm i}\frac{e^2}{4\pi\hbar^2}\ln\left(\frac{2E_{\rm F}-(\omega+{\rm i}\Gamma)\hbar}{2E_{\rm F}+(\omega+{\rm i}\Gamma)\hbar}\right). \quad (2)$$

Therefore, the surface conductivity σ of a graphene sheet can be written as[35,36]

$$\sigma(\omega) = {\rm i}\frac{e^2 k_{\rm B} T}{\pi\hbar^2(\omega+{\rm i}\Gamma)}\left(\frac{E_{\rm F}}{k_{\rm B}T}+2\ln({\rm e}^{-E_{\rm F}/k_{\rm B}T}+1)\right) + {\rm i}\frac{e^2}{4\pi\hbar^2}\ln\left(\frac{2E_{\rm F}-(\omega+{\rm i}\Gamma)\hbar}{2E_{\rm F}+(\omega+{\rm i}\Gamma)\hbar}\right). \quad (3)$$

We assume that the electronic band structure of the graphene sheet is not affected by the neighboring band structures, so the permittivity values of graphene for different Fermi energy values can be obtained from[35,36]

$$\varepsilon(\omega) = 1 + \mathrm{i}\frac{\sigma}{d\omega\varepsilon_0}, \tag{4}$$

where d is the thickness of graphene sheet and ε_0 is the permittivity in the vacuum.

2.1. Numerical results and discussion

In this section, we investigate the transmission property of graphene-based EIT metamaterial. We choose the geometrical parameters as follows: square lattice with period $l = 160$ nm, $s_1 = 70$ nm, $s_2 = 20$ nm, $w_1 = 43$ nm, $w_2 = 40$ nm, $g_1 = 20$ nm, $g_2 = 30$ nm, the thickness values of graphene and substrate are $d_1 = 1$ nm and $d_2 = 20$ nm, respectively. The relative permittivity of the substrate is set to be $\varepsilon_d = 3.3$. The mobility of graphene is taken to be $\mu_g = 6944$ cm^2/(V·s) and the temperature is room temperature $T = 300$ K. We can take the Fermi energy as $E_F = 0.6$ eV. The carrier scattering rate is taken to be $\Gamma = 2.4$ THz. Thus, with the above parameter values, the dielectric constant of graphene can be calculated by Matlab and the numerical calculations are carried out by using the commercial finite difference time-domain software package (CST Microwave Studio).

Figure 2 shows the transmission spectra of two different cut-wires serving as the bright modes under the electromagnetic field excitation. The curve in Fig. 2(a) (Fig. 2(b)) represents the transmission spectrum of the metamaterial composed of cut-wires shown on the left-hand side (the right-hand side) of Fig. 1(a). The cut-wires on the left-hand side (the right-hand side) exhibit an obvious transmission dip at 11.74 THz (10.15 THz) due to the electric resonance. As shown in Fig. 3, when the two different kinds of cut-wires are placed along the electric field direction, an EIT-like narrow transmission window with a transmission peak located between two dips is observed in the simulated transmission and the two cut-wires are excited by the electric field at the same time. The transmission peak at 10.95 THz exceeds 84% and two transmission dips are located at 10.36 THz and 11.67 THz. Because the excited two cut-wires are very weakly hybridized, the two resonance modes (10.36 THz and 11.67 THz) are close to their initial frequencies (10.15 THz and 11.74 THz) as shown in Fig. 2.

To better understand the physical meaning of the EIT-like transparency phenomenon, the current densities at two transmission dips and transmission peak are calculated and shown in Fig. 4. When frequency is 10.36 THz, only the right cut-wires are excited strongly by the electric field of incident waves, and the left cut-wires are excited very weakly as shown in Fig. 4(a). On the contrary, only the left cut-wires are excited by the electric field of incident wave strongly, and the right cut-wires are excited very weakly when frequency is 11.67 THz as shown in Fig. 4(c). Both cut-wires are excited simultaneously at 10.95 THz due to the resonance detuning, which is the characteristic of electromagnetically-trapped mode as shown in Fig. 4(b).

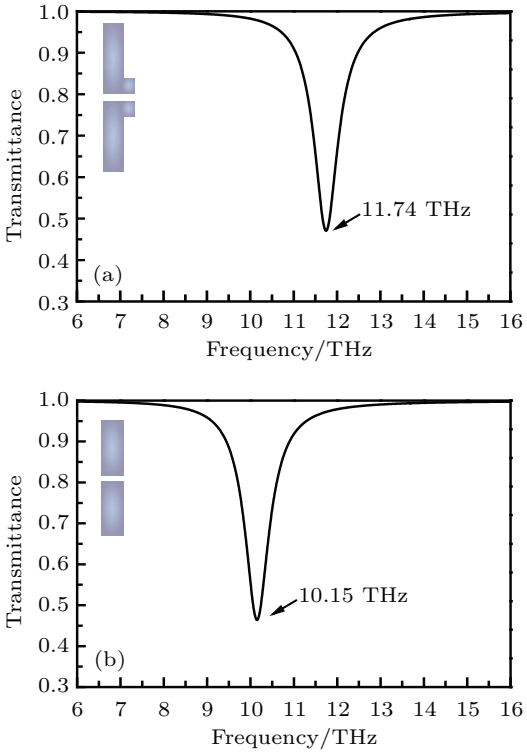


Fig. 2. (color online) Transmission coefficient for the cut-wires (a) on the left-hand side and (b) on the right-hand side.

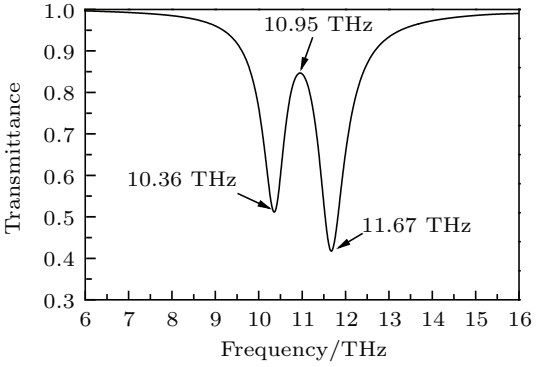


Fig. 3. Transmission of the metamaterial EIT at $E_F = 0.6$ eV.

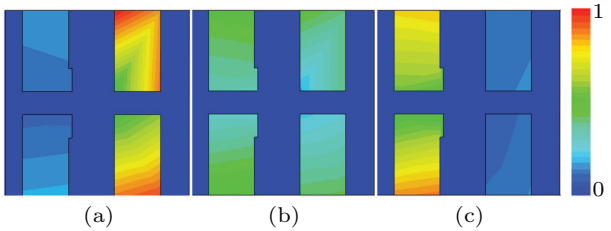


Fig. 4. (color online) Current density distributions on the unit cell, computed at frequencies of (a) 10.36 THz, (b) 10.95 THz, (c) 11.67 THz. The color scale is normalized between 0 and 1.

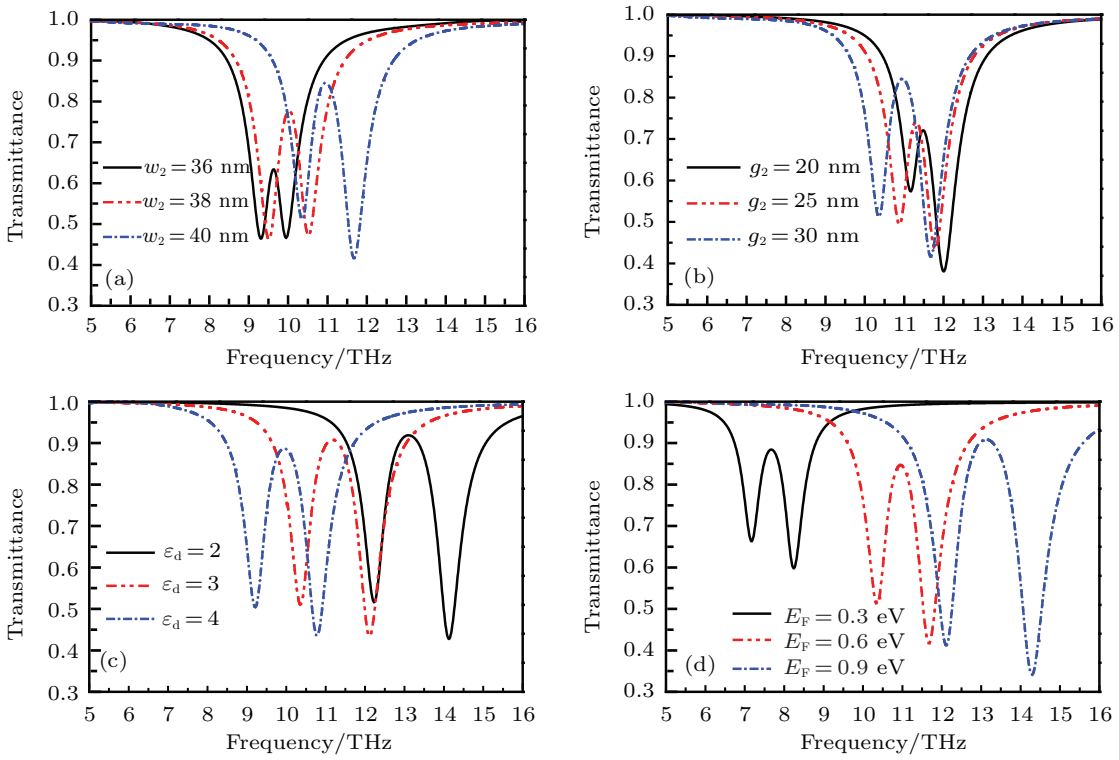


Fig. 5. (color online) Transmission spectra of the metamaterial EIT for various values of (a) w_2, (b) g_2, (c) ε_d, and (d) E_F.

The effect of geometrical dimension on the response of the EIT is characterized next. Figure 5(a) shows the transmission spectra for $w_1 = 36$ nm, 38 nm, and 40 nm. The other parameters are the same as those in the case of Fig. 1. With increasing w_1, the resonant frequencies of left cut-wire and right cut-wire will shift, respectively. Therefore, the transmission peak shifts to higher frequency and the transmission peak changes obviously. On the other hand, if g_2 is increased from 20 nm to 30 nm, the transmission peak of EIT shifts to lower frequency slightly. When $g_2 = 30$ nm, a higher transmission peak is obtained and the transmission band of EIT is larger than when g_2 has other values.

The effect of the substrate on the response of the resonator is characterized. For this set of simulations, the following parameter values are adopted: $l = 160$ nm, $s_1 = 70$ nm, $s_2 = 10$ nm, $w_1 = 43$ nm, $w_2 = 40$ nm, $g_1 = 20$ nm, $g_2 = 30$ nm, $d_1 = 1$ nm and $d_2 = 20$ nm, while ε_d is varied between 2 and 4. The transmittance of the resonator is computed for each of ε_d values as shown in Fig. 5(c). As ε_d is increased, it is clear that red shift can be observed, and the amplitude of the transmittance decreases gradually with the increase of ε_d.

As mentioned above, the most important advantage of the proposed structure is the tuneability of the graphene, which can be tuned by chemical doping and electrostatic gating. The transmission properties of the proposed metamaterial structure can be tuned by applying different bias voltages. Therefore, the designed structure can work at different frequencies without modifying the parameter of the physical structure. This is very important and practical in many practical applications compared with metal-based metamaterial structure. Because it is very difficult to change the parameter of the physical structure if the metamaterial has been fabricated. As shown in Fig. 5, It is obvious that the EIT-like transparency window can shift in a broad range by merely varying the Femi energy in the investigated frequency regime. As the Femi energy increases from 0.3 eV to 0.9 eV, the peak frequency of the transmission window can be tuned from 7.67 THz to 13.13 THz. Owing to the tuneability of transparency window, there are many important applications such as switches or modulators in the terahertz frequency band. For example, the transmission is about 35% at 14.34 THz if the Femi energy is 0.9 eV, while the transmission at 14.34 THz is tuned to be 98% when the Femi energy decreases to 0.6 eV. Therefore, the transmission could be switched between 35% and 98% by simply changing the Femi energy. As a consequence, a transmission magnitude modulation depth of 63% could be achieved by changing the Femi energy from 0.9 eV to 0.6 eV.

3. Conclusions

In this work, we investigate a tunable EIT-Like transmission in graphene-based metamaterial. The coupling induced indirectly by the incident electromagnetic wave results in an EIT-like transparency window in terahertz frequency range. The peak frequency of the transmission window is sensitive to geometrical dimension of the structure and permittivity of the substrate. Owing to the tuneability of the graphene, when the

Femi energy is changed through electrostatic gating, the EIT-like transparency window can shift over a broad range. With increasing Femi energy, the peak frequency of the transmission window is red-shifted. Therefore, the proposed structure can work at different frequencies without reconstructing the physical structure. These properties could have many important applications, such as switches or modulators in the terahertz frequency band.

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