Tunable Electromagnetically Induced Transparency Like Transmission in Graphene Metamaterials with Indirect Coupling

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Abstract— An novel graphene-based metamaterial with tunable electromagnetically induced transparency (EIT)-like transmission is numerically studied in this paper. The designed structure consists of a graphene layer composed of coupled cut-wire pairs printed on a substrate. The simulation confirms that an EIT-like transparency phenomenon occurs in the metamaterial owing to indirect coupling and the proposed structure can be used in terahertz frequency range. More importantly, the transparency windows for the structures with indirect coupling can be dynamically controlled over a broad frequency range by varying the Fermi energy levels of the graphene layer (through electrostatic gating). The proposed metamaterial structure offers an additional opportunity to design novel applications such as switching and modulators.

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]. Recently, many interests of researchers have been focused on the mimic classical EIT phenomenon by using metamaterial [2, 3]. 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 frequency, but it is difficult to achieve once the devices are fabricated. Obviously, how to obtain a tunable EIT has been the focus of the interest of the researchers recently.

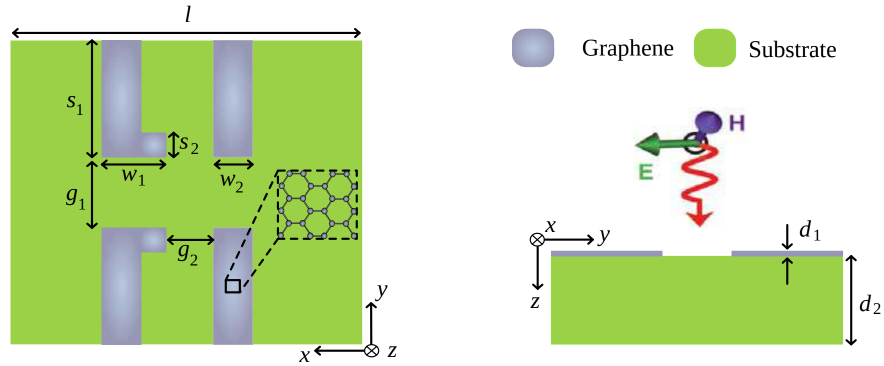
Graphene, which is a two-dimensional layer of carbon atoms arranged in a honeycomb pattern, has become a hot material in researches since it was discovered in 2004 [4, 5]. Its conductivity can be controlled by changing the Fermi energy levels. In this work, the graphene was introduced into the EIT metamaterial with indirect coupling. Therefore, the transparency windows for the structures with indirect coupling can be dynamically controlled over a broad frequency range by varying the Fermi energy levels of the graphene layer (through electrostatic gating) [6–8]. It is very convenient to tune the properties of the EIT comparing with other works. And the EIT-like phenomenon can be observed in terahertz frequency. The proposed graphene-based tunable EIT has some important potential practical applications.

2. THEORETICAL MODEL

The unit cell of the graphene-based EIT metamaterial we propose is plotted in Figure 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 placed 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 of the two resonant frequencies will be determined by the difference between w_1 and w_2. The thicknesses of graphene and substrate are d_1 and d_2. The array periodicities in both x and y directions are l. The relative permittivity of the substrate is defined as ε_d. The wave vector $\mathbf{K}(\omega)$ for incident wave is perpendicular to the xz plane.

The surface conductivity σ of graphene is the sum of the intraband σ_{intra} and the interband term σ_{inter}. Therefore, the surface conductivity of a graphene sheet $\sigma = \sigma_{intra} + \sigma_{inter}$ can be written as [9, 10]

$$\sigma(\omega) = i\frac{e^2 k_B T}{\pi\hbar^2(\omega + i\Gamma)}\left(\frac{E_F}{k_B T} + 2\ln\left(e^{-\frac{E_F}{k_B T}} + 1\right)\right) + i\frac{e^2}{4\pi\hbar^2}\ln\left(\frac{2E_F - (\omega + i\Gamma)\hbar}{2E_F + (\omega + i\Gamma)\hbar}\right) \quad (1)$$



(a) (b)

Figure 1: (a) Top view of the unit cell with dimensions. (b) Cross section view and the normally incident excitation.

where e is the charge of the electron, k_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, E_F is the Fermi energy in graphene.

We assume that the electronic band structure of the graphene sheet is not affected by the neighboring, so the permittivity of graphene for different Fermi energy values can be obtained by [9, 10]

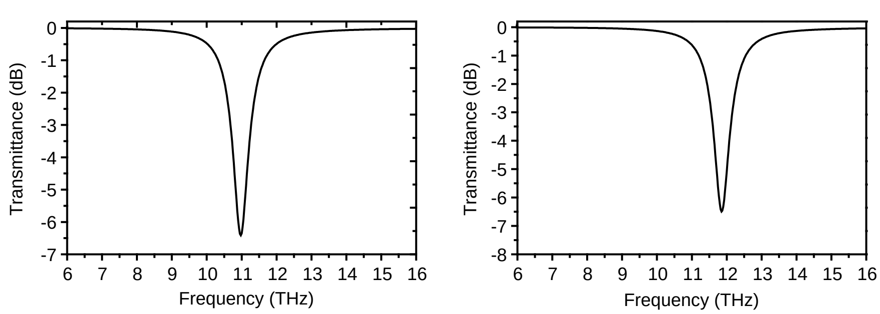
$$\varepsilon(\omega) = 1 + i\frac{\sigma}{d\omega\varepsilon_0} \tag{2}$$

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

3. NUMERIAL RESULTS AND DISSUSSION

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, $s_2 = 10$ nm, $w_1 = 50$ nm, $w_1 = 40$ nm, $g_1 = 20$ nm, $g_2 = 30$ nm. The thicknesses of graphene and substrate are $d_1 = 1$ nm and $d_2 = 20$ nm, respectively. The carrier scattering rate is taken to be $\Gamma = 2.4$ THz. The relative permittivity of the substrate is set to $\varepsilon_d = 3.3$. We can define the Fermi energy as $E_F = 0.6$ ev.

Figure 2 shows the transmission spectra of two different cut-wires serving as the bright modes under the electromagnetic field excitation. The curve in Figure 2(a) (Figure 2(b)) represents the transmission spectrum of the metamaterial composed of one kind of cut-wires shown in the left-hand side (the right-hand side) of Figure 1. The cut-wire in the left-hand side (the right-hand side) exhibits visible transmission dip at 10.98 THz (11.85 THz) owing to the electric resonance. As shown in Figure 3, when the two different kinds of cut-wires are placed along the electric field direction, an EIT-like narrow transmission window with transmission peak located between two dips is observed in the simulate transmission. The transmission peak at 11.13 THz exceeds 83% (−1.6 dB) and two transmission dips are located at 10.57 THz and 11.78 THz. Because the excited



(a) (b)

Figure 2: Transmission coefficient for (a) the cut-wire in the left-hand side and (b) the cut-wire in the right-hand side.

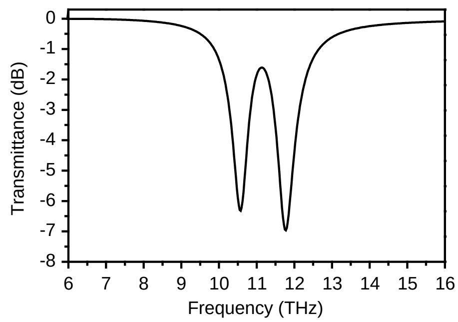


Figure 3: Transmission spectra of the metamaterial EIT.

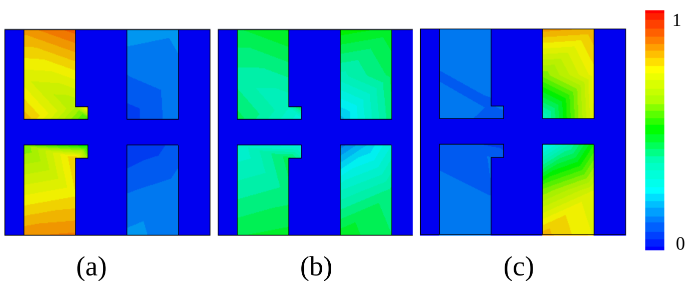


Figure 4: Current density distributions on the unit cell computed at frequencies: (a) 10.57 THz, (b) 10.98 THz, (c) 11.78 THz. The color scale is normalized between 0 and 1.

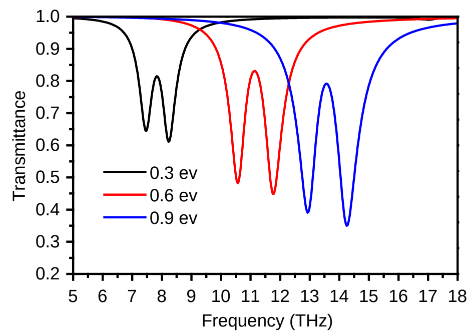


Figure 5: Transmission spectra of the metamaterial EIT for various of E_F.

two cut-wires are very weakly hybridized, the two resonance modes (10.57 THz and 11.78 THz) are close to their initial frequencies (10.98 THz and 11.85 THz) as shown in Figure 2.

To better understand the physical meaning of the EIT-like transparency phenomenon, the current density at two transmission dips and transmission peak are calculated which is shown in Figure 4. When frequency is 10.57 THz, only the left cut-wire is excited strongly by incident light, and the right cut-wire is excited very weakly, as shown in Figure 4(a). On the contrary, only the right cut-wire is excited by incident light strongly, and the left cut-wire is excited very weakly when frequency is 11.78 THz, as shown in Figure 4(c). Both cut-wires are excited simultaneously at 10.98 THz owing to the resonance detuning which is the characteristic of electromagnetically-trapped mode, as shown in Figure 4(b).

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 designed structure can work at different frequencies without modifying the parameter of the physical structure. This is very important and practical in the many practical applications comparing with metal-based metamaterial structure. Because it is very difficult to change the parameter of the physical structure if the structure is fabricated. As shown in Figure 5, It is obviously that the EIT-like narrow transparency window can be shifted over a broad range by merely varying the Femi energy in the investigated frequency regime. As the Femi energy is increased from 0.3 ev to 0.9 ev, the peak frequency of the transmission window can be tuned from 7.83 THz to 13.58 THz. Due to the tuneability of transparency windows, there are many important applications such as switches or modulators in the terahertz frequency band. For example, the transmission is about 35% at 14.3 THz if the Femi energy is 0.9 ev, while the transmission at 14.3 THz is tuned to be 97.6% when deceasing Femi energy to 0.6 ev. Therefore, the transmission could be switched between 35% and 97.6% by simply changing the Femi energy. As a consequence, a transmission magnitude modulation depth of 62.6% could be achieved by changing the Femi energy from 0.9 ev to 0.6 ev.

4. CONCLUSION

In summary, a tunable EIT-Like transmission in graphene-based metamaterial with indirect coupling is proposed. The coupling induced indirectly by the incident electromagnetic wave results in an EIT-like narrow transparency window in terahertz frequency range. Due to the tuneability of the graphene, when the Femi energy is changed through electrostatic gating, the EIT-like narrow transparency window can be shifted over a broad range. Increasing Femi energy red-shifts the peak frequency of the transmission window. Therefore, the proposed structure can work at different frequencies without reconstructing the physical structure. These properties could be applied in many important applications, such as switches or modulators in the terahertz frequency band.

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