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Dynamically tunable implementation of electromagnetically induced transparency based on bright and dark modes coupling graphene-nanostrips

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ABSTRACT

In this paper, we numerically demonstrated a dynamically tunable implementation of electromagnetically induced transparency (EIT) based on bright and dark modes coupling graphene-nanostrips. Two graphene-nanostrips are connected respectively with two metallic pads, which make Fermi energies of proposed two graphene-nanostrips can be independently tuned by changing bias voltage between the metallic pads and substrate, and the EIT window can be easily controlled than metallic and separated graphene structures. As a result, the EIT window has a significant tunable capacity, and the most remarkable characteristic of proposed structure is to achieve distinct transparency windows respectively at two perpendicular directions of polarization, which is not obtained or analyzed in the previous similar structures, and these merits exhibit the potential applications in sensor device.

1. Introduction

Electromagnetically induced transparency (EIT) is a quantum coherent effect in atomic system, in which transparency window is obtained and the electromagnetic (EM) waves pass through it with property of slow light effect [1]. While the applications of EIT in practice are limited due to the scathing experiment requirements conditions, such as low temperature [2,3]. Recent discoveries of analogues of EITs have tremendous attentions in metamaterials, the EIT-like in metamaterial have significant advantages and wider application due to it can overcome the scathing experiment conditions and make use of the unique properties of metamaterials [4–7], and it is usually achieved by near-field coupling and phase coupling, the near-field coupling scheme for EIT generations have two kinds of schemes: bright–bright mode coupling and bright–dark mode coupling [8]. So far various metamaterials-based EIT-like have been proposed and potential applied in slow-light control [9,10], biochemical sensing [11,12], nonlinear optics devices [13–15], and so on.

Currently, from the viewpoint of the practical application, tunable EIT-like effect has been intensively investigated since it can be used to expand the operating frequency range and more potential applications [16]. Instead of reducing the geometric parameters of schemes, different approaches have been proposed to realize tunable EIT window [17–24]. As an alternative method, graphene has attracted considerable attention due to its unique properties, particularly the conductivity of graphene can be easily controlled by varying the Femi energy E_F through altering the bias voltage, which make EIT-like structures based on graphene more significant advantages than metallic structures [25]. Recently, many EIT-like structures based on graphene have been proposed and numerically investigated for dynamically tuning of the EIT resonance effect [26–32]. These results demonstrate that the controllability of graphene would open up new approaches for actively controlling EIT-like systems. However, most of these transparency windows are observed at the incident waves polarizing along the single direction, and the transparency window will disappear as the direction of polarization is changed, which will hinder the flexible and universal applications of EIT-like in sensors, thus it is very essential to investigate the EIT-like structure with the characteristic of multiple directions of polarization or polarization independent.

In this paper, based on near-field coupling between the dark mode and the bright mode, a planar complementary graphene nanostructure to achieve the dynamically tunable electromagnetically induced transparency in terahertz regions is proposed. The nanostructure has two hybrid graphene-nanostrips, and the left graphene-nanostrip (LGN) has

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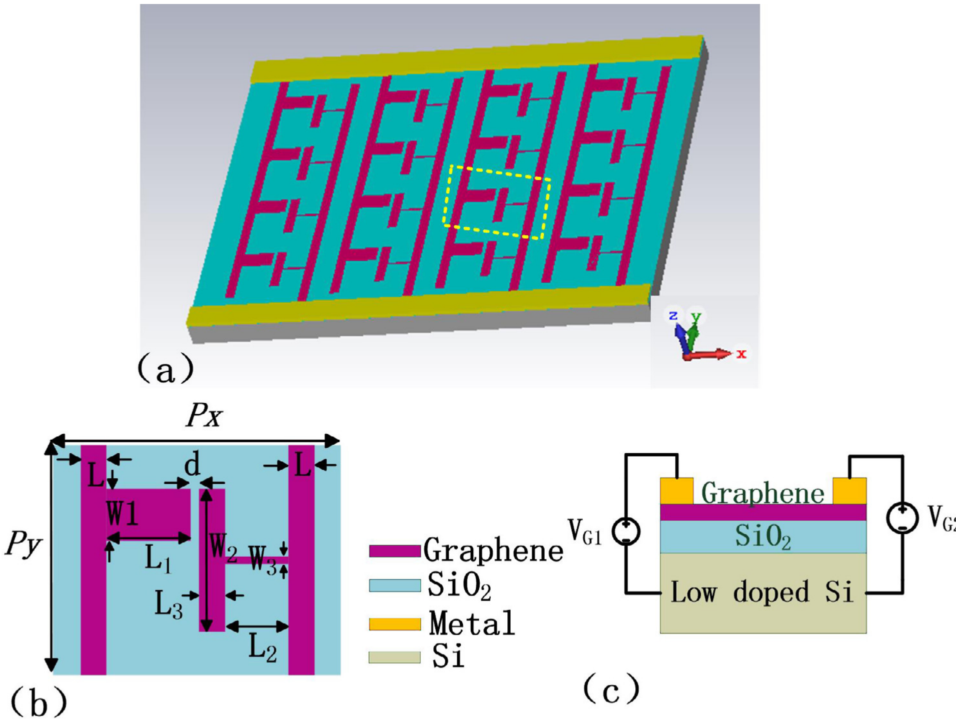

Fig. 1. EIT structure based on the hybrid graphene metamaterial: (a) schematic of hybrid graphene metamaterial, (b) close-up view of unit cell, and (c) cross-sectional view of unit cell.

a horizontal graphene strip, electrically connected by a continuous vertical graphene wire, the right graphene-nanostrip (RGN) has a vertical graphene strip, electrically connected with another continuous vertical graphene wire by a horizontal graphene strip, each continuous vertical graphene wire is separated and connected respectively with the corresponding metallic pads. Compared to the previous structures, the proposed nanostructure can dynamically control the transparency windows peak at various frequencies by independently varying the Fermi energies of two graphene-nanostrips without reoptimizing and refabricating the structure, the most remarkable characteristic of proposed structure is the transparency window could be observed at the incident waves polarizing along the x-direction and y-direction, which is not obtained or analyzed in the previous similar structures [29,31,32], and it has different mechanism with the phase coupling scheme for EIT generations using graphene [33]. Therefore, the proposed complementary graphene nanostructure with tunable EIT response at two perpendicular directions of polarization exhibits the potential applications in sensor device.

2. Structure design and simulation

The schematic of the proposed hybrid graphene nanostructure is shown in Fig. 1 The unit cell is composed of two hybrid graphene-nanostrips, and the left graphene-nanostrip (LGN) has a horizontal graphene strip, electrically connected by a continuous vertical graphene wire, the right graphene-nanostrip (RGN) has a vertical graphene strip, electrically connected with another continuous vertical graphene wire by a horizontal graphene strip, the LGN and RGN are fabricated on the low doped silicon substrate covering with the thin SiO_2 layer (as shown in Fig. 1(c)), each continuous vertical graphene wire is separated and connected respectively with the corresponding metallic pads (as shown in Fig. 1(a)). The LGN (as shown in Fig. 1(b)) has a horizontal graphene strip with L1 = 6.5 μm, and W1 = 3.66 μm, while the RGN (as shown in Fig. 1(b)) has a vertical graphene strip with W2 = 5.08 μm, and L3 = 2 μm. The unit cells are arranged in a periodic array with periodic length Px = 23 μm, Py = 16 μm, other structural parameters are as follows: L = 2 μm, L2 = 5 μm, W3 = 0.5 μm, d = 0.5 μm, while the thicknesses of the SiO_2 layer and silicon substrate are 30 nm and 1 μm respectively.

In order to explore EIT-like response of the hybrid graphene nanostructure, numerical calculations based on finite difference time domain (FDTD) method are performed, where periodic boundary conditions is used for a unit cell in x- and y-directions, and z-plane has a perfectly matched layer boundary condition. The plane waves polarizing along x-direction and y-direction respectively are normally incident to the structure along the-z direction, as shown in Fig. 1(a). In our calculations, the permittivity of SiO_2 and Si substrate are taken as 3.9 and 11.7 respectively. To simplify the numerical calculations, the graphene to be an effective medium with a relative complex permittivity of $\varepsilon_r(\omega) = 1 + j\,\sigma(\omega)\,/\,(\omega\varepsilon_0\, t)$, in which the thickness t = 0.34 nm and the complex surface conductivity $\sigma(\omega)$ can be described as [34]:

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

where, k_B is the Boltzmann's constant, E_F represents the Fermi energy of graphene, ε_0 is the permittivity of vacuum, ω is the angular frequency of incident wave, T is the temperature of the environment (T = 300 K), e is the charge of an electron, $\hbar = h/2\pi$ is the reduced Planck's constant, $\Gamma = ev_f^2/(\mu E_F)$ is the scattering rate, where $v_f = 10\ ^6\mathrm{ms}^{-1}$ is Fermi velocity, and μ = 10 000 $\mathrm{cm}^2\ \mathrm{V}^{-1}\mathrm{s}^{-1}$ is carrier mobility [26,30,33]. Compared to the metal-based structures or separated graphene structures, the Fermi energies of proposed two graphene-nanostrips can be independently tuned by changing bias voltage V_{g1} or V_{g2} (as shown in Fig. 1(c)) between the metallic pads and silicon substrate. Based on destructive interference between the dark mode and the bright mode, as a result, the EIT window could be observed and dynamically dual tuned at the incident waves polarizing along the x-direction and y-direction.

3. Results and discussion

To investigate the EIT-like effect of proposed graphene nanostructure, the isolated LGN and RGN in EIT structure are initially investigated to clarify underlying forming process of the EIT window, as shown in Fig. 2, According to Fig. 2(a), the isolated RGN resonates at 1.25 THz (demonstrated by the red line), while the LGN is inactive (demonstrated