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Active manipulation of electromagnetically induced reflection in complementary terahertz graphene metamaterial

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ABSTRACT

A graphene-based metamaterial,featuring a dynamically tunable terahertz electromagnetically induced reflection (EIR) window, is numerically investigated in this paper. The designed metamaterial consists of a graphene single layer perforated with wire–slot pair array and a split-ring resonator slot (SRR-slot) structures printed on a SiO_2/Si substrate, where the wire–slot pair and SRR-slot structures can act as the superradiant and subradiant elements, respectively. The surface current distributions demonstrate that the destructive interference caused by strong near field coupling between two resonators can induce a sharp reflection peak. Through varying lateral displacement between two resonators within the unit cell, moreover, the reflection peak amplitude and the corresponding group delay can be actively controlled due to the electromagnetic energy transfer between two resonators. In addition, the reflection peak can also exhibit obvious blue-shift by changing Fermi energy of graphene. Therefore, the work opens up the possibility for the development of compact terahertz elements such as modulators, switches and slow light devices.

1. Introduction

Recently, the metamaterial-based electromagnetically induced transparency (EIT) effect has attracted considerable attentions due to the potential applications in optical delay lines [1], slow light components [2], and highly sensitive sensors [3]. Compared with the traditional EIT effect in atomic system, the EIT effect in metamaterial system can be realized by different ways, such as optical dipole antennas [4], trapped-mode patterns [5], and split-ring resonators [6]. These methods can not only avoid the stringent experimental requirements in atomic system, and but also make use of the unique property of metamaterial [7]. So far, various metamaterial-based EIT structures have been proposed and experimentally demonstrated from microwave to optical frequencies [8–13]. Unfortunately, most of these metamaterial structures can only work at a narrow wavelength range, which severely hampers the development and application of EIT-like effect [14].

To actively tuning EIT window, currently, various approaches have been employed and demonstrated by integrating metamaterials with active materials [15–18]. For example, a thermally tunable EIT window was experimentally demonstrated in asymmetric superconductor metamaterial [15]. An optically reconfigurable EIT effect was reported through incorporating Si islands into the metamaterial unit cell [16]. Recently, Micro-Electro-Mechanical Systems (MEMS) technology is also proposed to realize controllability of EIT window [17,18]. However, those tunable methods depend highly on the nonlinear property of active materials, resulting inevitably in low modulation depth and range. In addition, the possibility and reliability for the massive fabrication based on the MEMS technology are still limited by the complex structure and process.

Since discovered in 2004, graphene has attracted wide attentions due to unique properties [19]. More importantly, the conductivity of graphene can be actively tuned by chemical or electrostatic doping [14]. Currently, variously tunable graphene-based metamaterials have been reported by patterning, stacking or integrating graphene [20–25]. In this paper, a complementary terahertz graphene metamaterial, consisting of periodically arranged graphene wire–slot pair and SRR-slot structures

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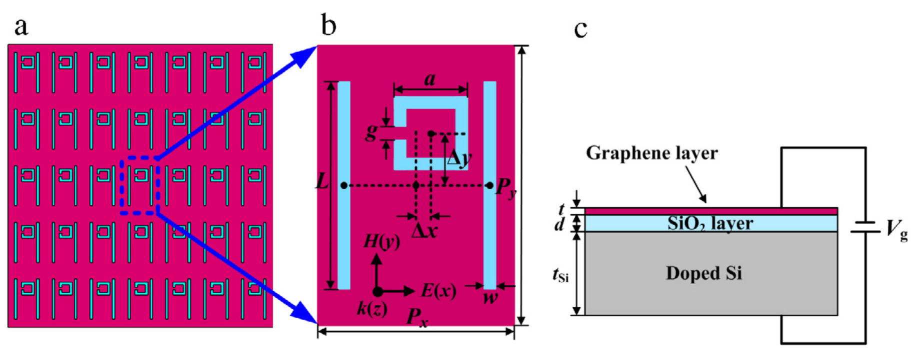

Fig. 1. EIT structure based on the complementary graphene metamaterial: (a) schematic of the complementary graphene metamaterial, (b) close-up view of unit cell, and (c) cross-sectional view of unit cell.

printed the SiO_2/Si substrate, is designed and numerically studied. An EIR window can be obtained in the complementary metamaterial due to near field coupling between two resonators of unit cell. Moreover, the EIR window and the associated group delay can be actively tuned by changing the lateral displacement between two resonators and Fermi level of graphene. Therefore, the proposed complementary graphene-based metamaterial with tunable EIR window can exhibit the potential applications in light storage, modulators, tunable sensors and switchers.

2. Design and simulation of EIR structure

Fig. 1(a) schematically depicts the designed complementary graphene metamaterial at terahertz range. The unit cell of the designed metamaterial is composed a graphene wire–slot pair structure and a graphene SRR-slot structure printed on a light doped silicon substrate covering with the thin SiO_2 layer, which act respectively as the superradiant and subradiant elements, as shown in Fig. 1(b). Compared with the previous structures [3,13,26], two resonator elements can be simultaneously excited with electric field excitation along x-direction, producing strong near field coupling each other. As a result, the destructive interference resulting from strong near field coupling between two resonators induces the sharp EIR window. More importantly, the EIR window can be actively tuned by applying a bias voltage between the graphene layer and the substrate without reconstructing the physical structure or imbedding other actively controlled materials, as shown in Fig. 1(c).

In order to explore EIR response of the complementary graphene metamaterial, numerical calculations based on finite difference time domain (FDTD) method are performed, where periodic boundary conditions are used in x- and y-directions, and perfectly matched layer boundary condition is applied in z plane. The plane wave polarizing along x-direction is normally incident to the structure surface along z-direction, as shown in Fig. 1(b). In numerical calculations, the lateral displacements of the SRRs-slot structure with respect to the wire–slot pair structure are defined as Δy and Δx respectively, and other structural parameters are as following: P_x = 80 μm, P_y = 120 μm, L = 85 μm, $w = g$ = 5 μm, and the thicknesses of the SiO_2 layer and silicon substrate are 300 nm and 300 um, respectively, while the relative permittivities of the SiO_2 layer and silicon substrate are taken as 3.9 and 11.7 respectively. To simplify numerical calculations, in addition, we assumes the graphene to be an effective medium with thickness of t = 0.34 nm and relative complex permittivity of $\varepsilon_r(\omega) = 1 + j\sigma(\omega)/(\omega\varepsilon_0 t)$, in which the conductivity $\sigma(\omega)$ can be described as [27–29]:

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

where ε_0 is the permittivity of vacuum, ω is the frequency of incident wave, E_F is the Fermi energy, Γ is the scattering rate, T is the temperature of the environment (T = 300 K), e is the charge of an electron, k_B is the Boltzmann's constant, and $\hbar = h/2\pi$ is the reduced Planck's constant.

3. Results and discussions

3.1. Mechanism of EIR window

To clarify EIR response in the complementary graphene metamaterial, the reflection spectra of three different structures, which are the isolated graphene wire–slot pair array, the isolated graphene SRR-slot array, and their combined array (EIR structure), are calculated respectively, as shown in Fig. 2. When the incident magnetic field H is oriented along the y-axis (as shown in Fig. 1(b)), the isolated graphene wire–slot pair structure and isolated graphene SRR-slot structure with E_F = 0.5 eV can excite two resonances with different Q-factor at 0.96 THz, as shown in Figs. 2(a) and 2(b). For example, the isolated wire–slot pair structure appears a broader localized surface plasmon resonance (LSPR) with the Q-factor of 3.11 due to strong coupling with incident terahertz wave. By contrast, the isolated SRR-slot structure shows a narrower LC resonance with the Q-factor of 56.83 because of weak coupling with incident terahertz wave. As expected, the wire–slot pair structure and SRR-slot structure can act as the superradiant and subradiant elements, respectively. When two slot-type resonators are integrated within a unit cell to construct a EIR structure with the lateral displacements of Δy = 0 μm and Δx = 0 μm, and E_F = 0.5 eV, however, a sharp reflection peak with the amplitude of 83% and Q-factor of 86.6 is obtained at 0.97 THz due to strong near field coupling between two resonators, as shown in Fig. 2(c).

To better understand the occurrence of the EIR peak, the surface current distributions of three structures at the reflection dip or peak are calculated respectively, as shown in Fig. 3. For the isolated wire–slot pair structure, the surface currents are mainly focused at both ends of the wire-slot structure (see Fig. 3(a)), inducing a dipolar LSPR with lower Q-factor (as shown in Fig. 2(a)). For the isolated SRR-slot structure, the loop currents in the inductive surrounding graphene are concentrated around the SRR-slot structure (see Fig. 3(b)), while the charges are accumulated at the regions of the capacitive anti-rings (no shown here), as a result, exciting a LC resonance with higher Q-factor (as shown in Fig. 2(b)). Therefore, such surface current oscillations near the isolated wire–slot pair and SRR-slot structures correspond to the excitations of superradiant and subradiant modes, respectively. For the EIR structure in Fig. 3(c), however, we observe that the surface currents near the wire–slot pair structure are obviously suppressed due to the near field coupling between two slot-type resonators, as a result, the destructive interference from near field coupling between two resonators induces a sharp reflection peak in reflection spectrum (as shown in Fig. 2(c)).

3.2. Structural parameter dependence of EIR window

In order to further investigate near field coupling effect in the EIR structure, we perform the parametric study by varying the lateral displacement Δy and Δx, respectively. Fig. 4 shows the reflection spectra of the EIR structure with various Δy from 0 μm to 29 μm. It is