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Active manipulation of electromagnetically induced transparency in a terahertz hybrid metamaterial

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ABSTRACT

The metamaterial analogue of electromagnetically induced transparency (EIT) in terahertz (THz) regime holds fascinating prospects for filling the THz gap in various functional devices. In this paper, we propose a novel hybrid metamaterial to actively manipulate the resonance strength of EIT effect. By integrating a monolayer graphene into a THz metal metamaterial consisting of a split ring resonator (SRR) enclosed within a larger closed ring resonator (CRR), an on-to-off modulation of the EIT transparency window is achieved under different Fermi levels of graphene. According to the classical two-particle model and the distributions of the electric field and surface charge density, the physical mechanism is attributed to the recombination effect of conductive graphene. This work reveals the universal interaction of the monolayer graphene on the SRR and offers a new perspective towards designing THz functional devices.

1. Introduction

The EIT effect has received enormous attention due to the great potential in applications including slow light and nonlinear effects. EIT was first discovered in a three-level atomic system where the destructive quantum interference between a pump and a probe laser beam results in a narrow transparency window within a broad absorption profile [1]. However, the applications of EIT are severely hindered due to the cumbersome experimental conditions involved with the low temperature environment and high intensity lasers. Recently, the advent of metamaterial which possesses the ability to manipulate light–matter interaction in artificially designed structures creates the possibility to mimic the EIT effect in classical optical system [2,3]. Particularly, the metamaterial analogue of EIT at THz frequencies has been widely investigated since it offers an exciting way to fill the THz gap in biosensing, optical modulation and slow light devices [4–10].

In practice, it is highly desired to achieve the active manipulation of EIT resonance since it provides more dimensions to the designs and functionalities of metamaterial. Very recently, the integration of active materials into the metamaterial unit cell has been reported as the access route for the realization of dynamically controllable EIT resonance [11–16]. For example, Gu et al. integrated the photoconductive silicon into the metal metamaterial and allowed for a giant switching of the EIT resonance under the ultrafast optical pump-terahertz probe measurements [12]. Cao et al. experimentally demonstrated an amplitude modulation of EIT resonance in a hybrid metamaterial by including a thermally active superconductor resonator and a metal resonator in the unit cell [13]. The emerging graphene is an active material since its conductivity can be continuously tuned by changing the Fermi level via chemical or electrostatic gating [17–19]. Graphene metamaterial provides an alternative platform to realize the active manipulation of EIT resonances [20–29]. However, unlike the above-mentioned hybrid metamaterial, most reported graphene metamaterials shifted the resonance frequency rather than the strength of the EIT resonance, which gives rise to additional noises at adjacent frequency spectra in the modulation process. On the other hand, the nanostructured graphene in the metamaterial unit cell is in the discrete shape, posing great challenges for the nanoscale fabrication and the tunability implementation in practice. The monolayer graphene has also been suggested to integrate into the metal metamaterial to actively manipulate EIT resonance using its plasmonic response at THz frequencies, solving the latter problem to a great extent [30,31]. However, these works still focused on the active manipulation of the resonance frequency rather than the strength of

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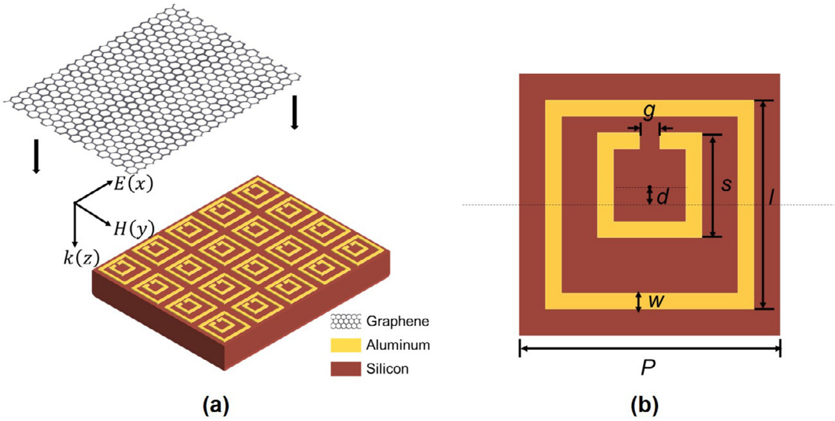

Fig. 1. The schematic illustration of the proposed hybrid EIT metamaterial. (a) Three dimensional schematic of the hybrid graphene-metal metamaterial. (b) The top view of the aluminum-based unit cell. The geometrical parameters are as follows: $P = 50$ μm, $l = 40$ μm, $s = 20$ μm, $w = 3$ μm, $g = 4$ μm, $d = 4$ μm.

the EIT resonance, which would introduce additional noises at adjacent frequency spectra in the modulation process. Very recently, our group and Zhang's group proposed a novel kind of hybrid metamaterial with a monolayer graphene under the dark mode resonators and realized active modulation of the resonance strength of the transparency window while maintaining the resonance frequency, which is attributed to the change in the damping rate of the dark mode resonator by the recombination effect of the conductive graphene [32,33]. However, these works only considered the interaction between the monolayer graphene and the EIT resonance from near field bright and dark coupling effect, the equally important case, namely, that between graphene and EIT from bright and quasi-dark (also called bright and bright) coupling effect is yet to be fully investigated.

In this work, we demonstrate an active manipulation of EIT resonance through integrating a monolayer graphene into a THz metal metamaterial. Here we take into consideration of another important kind of EIT metamaterials composed of coupled bright and quasi-dark mode resonators, instead of bright and dark mode resonators in our previous investigation. According to the simulation results, an on-to-off modulation of the resonance strength of EIT response can be achieved by shifting the Fermi level of graphene. Based on the two-particle model, the influence of the increasing Fermi level of graphene on the transmission amplitudes of the EIT resonance is theoretically investigated, and an excellent agreement between the theoretical fittings and the simulated results is observed. The distributions of the electric field and surface charge density provide a deeper insight into the modulation mechanism that the active manipulation of the proposed EIT metamaterial is attributed to the recombination effect of the conductive graphene. This work not only reveals the universal interaction of the monolayer graphene on the SRR, but also opens a new perspective towards designing compact and active sensors, slow light devices and switches in the THz regime.

2. Design and simulation of EIT structure

The schematic of the proposed hybrid EIT metamaterial is illustrated in Fig. 1. The unit cell consists of a SRR enclosed within a larger CRR on a semi-infinite silicon substrate. The SRR is square shaped with $s = 20$ μm in arm length and $w = 3$ μm in width, and leaves the gap on the upper side arm with $g = 4$ μm in length. The CRR also shows square shape and is $l = 40$ μm in arm length and $w = 3$ μm in width. The SRR is positioned close to the upper arm of the CRR with the vertical displacement of $d = 4$ μm away from the center of the unit cell. Both the SRR and CRR are made of aluminum with a thickness of 200 nm and are periodically arranged with a lattice constant $P = 50$ μm in both the x and y directions. The resonators are designed to exhibit very close resonance frequencies and highly contrasting resonance linewidths for EIT response in the THz regime. Furthermore, to achieve the active manipulation in the proposed EIT metamaterial, the monolayer graphene is placed on the top of the aluminum-based SRR and CRR.

The numerical simulations with the finite difference time-domain method (FDTD Solutions, Lumerical Inc., Canada) are performed using the periodical boundary conditions in the x and y directions and perfectly matched layers absorbing conditions in the z direction along the incident plane wave. In the simulations, the moderate mesh accuracy 4 is adopted to make good tradeoff between accuracy, memory requirements and simulation time. The silicon substrate has the refractive index of $n_{Si} = 3.42$. The aluminum has the optical constant at THz frequencies described by a Drude model,

$$\varepsilon_{Al} = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\omega\gamma}, \tag{1}$$

where the plasmon frequency $\omega_p = 2.24 \times 10^{16}$ rad/s and the damping constant $\gamma = 1.22 \times 10^{14}$ rad/s [34]. The optical conductivity of graphene σ modeled within the random-phase approximation consists of interband and intraband contributions. In the lower THz regime, the intraband contribution dominates and the interband contribution is negligible. Without the loss of generality, the graphene conductivity can be derived by a Drude-like model [35,36],

$$\sigma_g = \frac{ie^2 E_F}{\pi\hbar^2(\omega + i\tau^{-1})}, \tag{2}$$

where e is the electron charge, E_F is the Fermi level of graphene, $\hbar$ is the reduced Planck constant, ω is the angular frequency. $\tau = \mu E_F/(e v_F^2)$ is the carrier relaxation time dependent upon the carrier mobility μ and the Fermi velocity v_F[37,38]. In our simulations, $\mu = 3000$ cm^2/V·s and $v_F = 1.1 \times 10^6$ m/s from the experimental measurements are employed [39,40]. As can be seen from Eq. (2), shifting the Fermi level E_F enables the dynamic control of the graphene conductivity.

3. Results and discussions

To clarify the physical mechanism of the generation of the EIT resonance, three sets of arrays with the aluminum-based unit cell composed of the isolated CRR, the isolated SRR and the proposed EIT structure are investigated. With the plane wave propagation along the z direction and the electric field polarized in the x direction, the transmission spectra and field distributions of the three arrays are calculated respectively. The isolated CRR array and the isolated SRR array show independently excited resonances with transmission dips centered around the frequency at about 1.0 THz. As shown in Fig. 2, the isolated CRR array displays a broad resonance with Q factor (defined as the ratio of resonance frequency to the bandwidth at 3 dB) of 1.04 at 1.14 THz. Accordingly, a symmetric distribution of the opposite charges