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Implementation of selective controlling electromagnetically induced transparency in terahertz graphene metamaterial

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A terahertz electromagnetically induced transparency (EIT) metamaterial, consisting of single-layer graphene cut wire resonator arrays with closely placed graphene closed ring resonator arrays, was designed and numerically investigated in this paper. A distinct transparency window resulting from the near field coupling between two resonators can be obtained in the transmission spectrum. More importantly, since two resonator elements of all unit cells connect respectively with the corresponding metallic pads (Pad 1 and Pad 2) by the separated graphene wires, the location and amplitude of the transparency window, and the associated group delay and delay bandwidth product can be actively controlled by the selective doping graphene. Moreover, compared with other separated graphene patterns, a more convenient and fast modulation can be realized by applying gate bias voltage. In addition, a two-particle model was employed to theoretically study EIT behaviors of the graphene metamaterial with different doping states, and the analytic results agree excellently with our numerical results. Therefore, the work could offer a new platform for exploring actively tunable slow light terahertz devices such as modulators, buffers, and optical delays.

1. Introduction

Electromagnetically induced transparency (EIT) was first observed in a three level atomic system, which resulted from the quantum destructive interference between two different excitation pathways [1]. Recently, the EIT-like behavior can be also implemented in metamaterials composed of periodic sub-wavelength unit cell structure array [2]. Currently, a variety of EIT metamaterials have been developed due to potential applications in slow-light devices, sensing, and quantum information storages [3–5]. Unfortunately, most of these EIT windows obtained can only work at a fixed wavelength range, which severely limits the developments and applications of the EIT-like effect [6]. Therefore, active manipulation of EIT window is highly desirable for practical applications, such as tuning the dispersion and group velocity of light [7].

Generally, dynamic manipulation of EIT window in the coupled resonator systems depends mainly on three parameters: resonant frequency of bright mode, resonant frequency of dark mode, and coupling distance between two modes [8]. According to this principle, currently, many approaches to tuning EIT behavior have emerged in a passive manner by changing the incident angles [9,10] and in active manners by integrating metamaterials with active materials or components [11–13], as well as by tuning an external magnetic field [14]. Recently, the Micro-Electro-Mechanical Systems (MEMS) technology is also proposed to realize dynamic controllability of EIT window [15,16]. However, these approaches can only provide global control because of optical or thermal excitations, which hinders their multifunctional applications due to absence of selective control.

Since discovered in 2004, graphene has attracted considerable attention due to unique electric, mechanical, and thermal

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properties [17,18]. More importantly, the graphene conductivity can be dynamically tuned by doping [6]. Recently, different graphene-based tunable metamaterials have been reported by patterning, stacking or integrating graphene structures [19–21]. These results demonstrate that the active controllability of graphene is an ideal platform for realizing selective control of the coupled resonators in EIT-like systems. In this paper, we proposed a selectively controllable terahertz EIT metamaterial structure, unit cell of which consists of a graphene cut wire resonator with two closely placed graphene closed ring resonators. Moreover, two resonator elements of all unit cells connect respectively with the corresponding metallic pads by the separated graphene wires to realize selectively electrostatic doping. By selectively tuning Fermi energy of two resonators, the bandwidth, intensity and frequency of EIT window can be actively controlled as well as the associated group delay and delay bandwidth product. Therefore, the work would open up new avenues for designing tunable slow light terahertz devices.

2. Design and simulation of structure

For the traditional metal-based metamaterial EIT system, the amplitude modulation of EIT window can be obtained by changing the resonance strength of the dark mode [22] or tuning the coupling distance between the bright and dark resonators [23]. Here, a terahertz graphene metamaterial, patterned on a low doped silicon substrate with a thin SiO_2 layer, is proposed to realize active control of EIT window, as shown in Fig. 1(a). The metamaterial unit cell consists of a graphene cut wire resonator (GCWR) and two graphene closed ring resonators (GCRRs) acting as two bright modes with different Q-factors respectively, as shown in Fig. 1(b). Moreover, two resonator elements of all unit cells connect respectively with the corresponding metallic pads (Pad 1 and Pad 2) by the separated graphene wires to realize selectable doping, and the bias voltage applied to cut wire resonator and closed ring resonator is termed as V_{g1} and V_{g2} respectively, as shown in Fig. 1(c). Thus, Fermi energy of two resonators can be independently tuned by changing bias voltage (V_{g1} or V_{g2}) between the top gate and silicon substrate, realizing selective control of the near-field coupling strength between two resonators, as a result, the EIT window resulting from the near-field coupling can be actively tuned. Compared to the metal-based structures or separated graphene structures, however, this design can actively control and reconfigure the EIT window by selectively electrostatic doping without reconstructing the physical structure or imbedding other actively controlled materials.

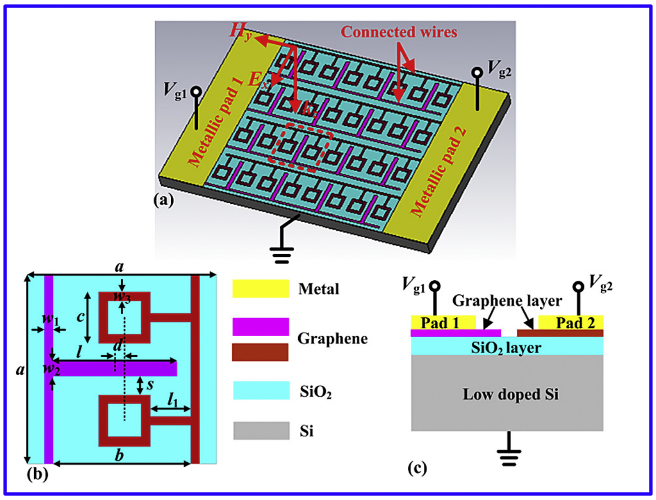

Fig. 1. EIT structure based on the terahertz graphene metamaterial: (a) schematic of graphene metamaterial, (b) close-up view of unit cell, and (c) cross-sectional view of unit cell. (A colour version of this figure can be viewed online.)

In order to explore EIT response of the proposed graphene metamaterial, numerical calculations based on finite difference time domain (FDTD) method are performed, where the periodic boundary condition of the unit cell is applied in x- and y-directions, while the perfectly matched layer boundary condition is set in z-direction. The plane wave polarizing along x-direction is normally incident to the structure surface along z-direction, as shown in Fig. 1(a). In our numerical calculations, the lateral displacement of the GCRRs structure with respect to the symmetry axis of the GCWR structure is defined as d, and the other structural parameters are as following: $a = 100$ μm, $b = 76$ μm, $c = 32$ μm, $d = 2$ μm, $l = 70$ μm, $l_1 = 27$ μm, $w_1 = 4$ μm, $w_2 = 8$ μm, $w_3 = 6$ μm, and $s = 7$ μm (as shown in Fig. 1(b)), while the thicknesses of the SiO_2 layer and silicon substrate are 300 nm and 300 μm, respectively. In addition, the relative permittivities of the SiO_2 and Si substrate are taken as 3.9 and 11.7 respectively. To simplify numerical calculations, we assume the graphene to be an effective medium with thickness of $t_g = 0.34$ nm and relative complex permittivity of $\varepsilon_r(\omega) = 1 + j\sigma(\omega)/(\omega\varepsilon_0 t_g)$, in which the conductivity $\sigma(\omega)$ can be described as [24]:

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

where ε_0 is the permittivity of vacuum, ω is the frequency of the incident wave, E_F is the Fermi energy, Γ is the scattering rate ($\Gamma = 2.4$ THz), 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. Forming principle of EIT window

Before studying the EIT-like structure shown in Fig. 1, two individual GCWR and GCRRs arrays in EIT structure are initially investigated to clarify underlying forming process of the EIT window, as shown in Fig. 2. For insolated GCWR array with Fermi energy of 0.2eV, a narrower resonance at 0.465 THz is directly excited by the incident wave when the excitation field is parallel to the GCWR structure (as shown in Fig. 2(a)). Moreover, the direction of the induced surface currents on GCWR structure are parallel to the excitation field, while strong electric fields are localized at one end of GCWR structure and the edges of the connected wire (as shown in Fig. 2(b) and (c)). Thus, both the field and current distribution patterns confirm a typical electric dipole mode. For isolated GCRRs array with Fermi energy of 0.2eV, in contrast, a broader resonance is excited at 0.515 THz due to strong coupling with the incident wave, as shown in Fig. 2(d). As a result, the surface currents on the connected wires and two arms of GCRRs structure parallel to the excitation field oscillate symmetrically, while strong electric fields are confined in two arm edges of the GCRRs structure perpendicular to the excitation field as well as both sides of the connected wire (as shown in Fig. 2(e) and (f)). When the excitation field is vertical to the connected wires, therefore, both GCWR and GCRRs structures can be simultaneously excited, inducing two electric dipolar resonances with different quality factors, as a result, an EIT