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Active modulation of electromagnetically induced transparency analogue in terahertz hybrid metal-graphene metamaterials

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ABSTRACT

Metamaterial analogues of electromagnetically induced transparency (EIT) have been intensively studied and widely employed for slow light and enhanced nonlinear effects. In particular, the active modulation of the EIT analogue and well-controlled group delay in metamaterials have shown great prospects in optical communication networks. Here we integrate a monolayer graphene into metal-based terahertz (THz) metamaterials, and realize a complete modulation in the resonance strength of the EIT analogue via manipulating the Fermi level of graphene. The physical mechanism lies in the active tuning of the damping rate of the dark mode resonator through the recombination effect of the conductive graphene. This work presents a novel modulation strategy of the EIT analogue in the hybrid metamaterials, and paves the way towards designing very compact slow light devices to meet the future demand of ultrafast optical signal processing.

1. Introduction

Electromagnetically-induced transparency (EIT) refers to the formation of a narrow transparency window within a broad absorption profile upon the application of an indirect excitation and the quantum destructive interference between the two excitation channels in a three-level atomic system[1]. This phenomenon is always accompanied by an extreme modification of the dispersion properties and thus potentially useful in many applications, such as slow light [2–4] and enhanced nonlinear effects [5,6]. However, realizing the conventional quantum EIT requires the stable optical pumping and often cryogenic temperature, whose complexities severely restrict practical applications, especially with respect to on-chip integration. These barriers have been overcome by considering that the underlying physics behind the EIT phenomenon is actually classical, and the analogue behaviors can be reproduced using coupled harmonic oscillators and RLC electric circuits [7,8]. This physical insight leads to the realization of the EIT analogues in a series of classical optical systems, such as coupled microresonators [9,10], photonic crystal waveguides [11,12], a waveguide side-coupled to resonators [13,14] and metamaterials [15–17], which are robust and free from the scathing experimental requirements of quantum optics. In particular, the metamaterial analogues of EIT through the near field coupling between the bright and dark mode resonators, have enabled the realization of this phenomenon at frequencies in radio-frequency (RF) [18–20], terahertz (THz) [21–26], near-infrared [27–29] and visible regimes [30,31] through defining a correspondingly tailored geometry for the unit cell. Due to the subwavelength thickness, these EIT analogues with the accompanying slow light and enhanced nonlinear effects have shown great prospects in designing very compact devices, such as optical filters [32,33], optical buffers [34,35] and ultrasensitive biosensors [36,37].

For practical applications, an active modulation of the EIT analogue and consequently the well-controlled group delay are highly desirable. To this end, an active metamaterial is a superior candidate. Up to now, a variety of strategies have been proposed to actively modulate the EIT analogues in metamaterial devices, such as mechanically reconfigurable metamaterials [38–40], hybrid metamaterials through integrating with photoactive semiconductors [41–44], superconductors [45,46], and phase change media [47–49]. As for hybrid metamaterials, in the

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milestonework [42] Gu J et al. demonstrated an active control of THz waves in classical EIT metamaterials at room temperature through integrating Silicon (Si) islands into functional unit cells and realized an on-to-off modulation of the EIT analogue by optical pump-terahertz probe (OPTP) measurements. However, the response time in this kind of modulation process is limited by the recovery time of the excited carriers in Si ($\sim$ 1 ms), which severely hinders applications in ultrafast optoelectronics. Graphene, a two-dimensional (2D) material with a plethora of exceptional electronic and photonic properties, has garnered enormous attention [50–52]. The relaxation time of the excited carriers in the monolayer graphene is on the order of picosecond, showing a promising future for ultrafast response [53,54]. Moreover, the conductivity of graphene can also be continuously tuned via manipulating its Fermi level by electric gating or photo-induced doping, which lays the direct foundation for efficient real-time control of resonance in metamaterials [55–63]. In the recent decade, a variety of graphene-based metamaterials have been proposed to realize the EIT analogues, where the nanostructured graphene can support the localized surface plasmon (LSP) resonance and act as the bright and dark mode resonators in the infrared and THz regimes [64–72]. However, on the one hand, it is the resonance frequency rather than the resonance strength of the transparency window will be tuned via manipulating the Fermi level of graphene in this kind of modulation process, therefore an on-to-off modulation of the EIT analogue at the specific resonance frequency without affecting adjacent frequency spectra can not be realized. On the other hand, the nanostructured graphene resonators in the isolated fashion can not be expediently tuned in practice and the ultrasmall feature size that corresponds to resonance entering into the THz gap is also challenging in the nanoscale fabrication. Very recently, the monolayer graphene has been proposed to integrate into the metal-based resonant metamaterials to actively modulate the EIT analogues using its plasmonic response in the infrared and THz regimes, addressing the latter concern to a great degree [73–76]. However, these pioneering works still mainly focus on the active modulation of the resonance frequency rather than the resonance strength of the transparency window, which may introduce additional noises at adjacent frequency spectra in the modulation process.

In the present work, we propose, for the first time to the best of our knowledge, an active modulation of the resonance strength of the EIT analogue in THz resonant metamaterials through integrating a monolayer graphene into the unit cell. The simulation results show that a complete modulation in the resonance strength of the EIT analogue can be realized at the specific resonance frequency without affecting adjacent frequency spectra via manipulating the Fermi level of graphene. The theoretical analysis based on the coupled harmonic oscillator model and distributions of the electric field and surface charge density reveal that the active modulation is attributable to the change in the damping rate of the dark mode resonator by the recombination effect of the conductive graphene. In addition, the well-controlled group delay accompanying EIT is also calculated for slow light applications. The picosecond-order response time of graphene facilitates the ultrafast optical modulation, and the monolayer morphology possesses the advantage of being easier to fabricate and manipulate, showing much better efficiency and feasibility than previous studies. Therefore, this work not only demonstrates the use of graphene in the THz hybrid metamaterials to the active modulation of the EIT analogue, but also paves the way towards designing very compact slow light devices with ultrafast response, which can play a vital role in the future THz communications.

2. The geometric structure and numerical model

The schematic illustration and geometric parameters of our proposed hybrid structure are shown in Fig. 1(a) and (b). Here we employ the classical structure to produce the EIT analogue, similar to [42]. The unit cell of Aluminum (Al)-based resonant metamaterials is arranged in a periodical array with lattice constants of $P_x = 80$ μm and $P_y = 120$ μm, and composed of a cut wire (CW) and a pair of identical but oppositely oriented split ring resonators (SRRs) on the top of a Si substrate. The CW is $L = 85$ μm in length and $W = 5$ μm in width; the SRRs are $l = 29$ μm in side length and $g = 5$ μm in split gap. The coupling distance between the CW and the SRRs is set to $s = 7$ μm. The thickness of both of the resonators is $t_{Al} = 200$ nm and the substrate is assumed to be semi-infinite. The optical properties of Al in the THz regime are described by the Drude model [77]

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

where the plasma frequency $\omega_p = 2.24 \times 10^{16}$ rad/s and the damping constant $\gamma = 1.22 \times 10^{14}$ rad/s. The refractive index of Si is taken as $n_{Si} = 3.42$.

The monolayer graphene is placed under the SRRs and can be modeled as a 2D flat sheet [78,79]. The graphene conductivity is derived using the random-phase approximation (RPA) in the local limit, including both the intraband and interband processes [80–82]

$$\begin{aligned}\sigma_g &= \sigma_{intra} + \sigma_{inter} \\ &= \frac{2e^2 k_B T}{\pi\hbar^2}\frac{i}{\omega + i\tau^{-1}}\ln\left[2\cosh\left(\frac{E_F}{2k_BT}\right)\right] + \frac{e^2}{4\hbar}\left[\frac{1}{2}\right. \\ &\quad \left. + \frac{1}{\pi}\arctan\left(\frac{\hbar\omega - 2E_F}{2k_BT}\right) - \frac{i}{2\pi}\ln\frac{(\hbar\omega + 2E_F)^2}{(\hbar\omega - 2E_F)^2 + 4(k_BT)^2}\right],\end{aligned} \tag{2}$$

where e is the charge of an electron, k_B is the Boltzmann constant, T is the operation temperature, $\hbar$ is the reduced Planck's constant, ω is the angular frequency of the incident light, τ is the carrier relaxation time and E_F is the Fermi level.

In the lower THz regime, the contribution originated from the interband process is negligible due to the Pauli exclusion principle when the Fermi level of graphene increases above half of the photon level. Here we only consider highly doped graphene with the Fermi level $E_F \gg k_BT$ and $E_F \gg \hbar\omega$, therefore graphene conductivity can be safely reduced to the Drude-like model [83,84]

$$\sigma_g = \frac{e^2 E_F}{\pi\hbar^2}\frac{i}{\omega + i\tau^{-1}}, \tag{3}$$

where the carrier relaxation time $\tau = (\mu E_F)/(e v_F^2)$ depends on the carrier mobility μ, the Fermi level E_F and the Fermi velocity v_F. Here we employ $\mu = 3000$ cm^2/V•s and $v_F = 1.1 \times 10^6$ m/s throughout the calculations, which are consistent with the experimental measurements [85,86].

As predicted by the equations (2) and (3), the graphene conductivity can be continuously tuned via manipulating its Fermi level. The fabrication and modulation processes follow the steps below [73,74]. Firstly, a monolayer graphene is grown on a copper foil using a chemical vapor deposition (CVD) method and subsequently transferred onto a Si substrate using Marble's reagent solution to remove the copper foil. Secondly, Al-based resonant