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A novel graphene metamaterial design for tunable terahertz plasmon induced transparency by two bright mode coupling

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ABSTRACT

A novel graphene-based metamaterial for terahertz plasmon induced transparency (PIT) is presented in this paper, which consists of a graphene ring and a graphene strip compound structure. Both the ring and strip are performed as bright modes which are induced by electric dipole resonances, respectively. The weak hybridization between two elements leads to a novel PIT window. The PIT window can be controlled by adjusting the geometric parameters of graphene-based metamaterial structure. More importantly, the resonant frequency of transparency window can be dynamically tuned over a broad frequency range by varying the Fermi energy of graphene through controlling the electrostatic gating instead of refabricating the structures. Correspondingly, through adjusting the Fermi energy of graphene, a large group delay could also be observed, reaching up to 0.5 ps at the transparent peak. These results may offer great promise for tunable terahertz switching, slow light device, and sensing technology.

1. Introduction

Electromagnetically induced transparency (EIT) is a quantum destructive interference between pumping and probing field, which occurs in three-level atomic system [1,2]. However, because of the specific experimental conditions such as cryogenic temperatures, coherent pumping and high intensities, the investigations and practical applications of the EIT in an atomic system are significantly constrained [3]. Compared with the EIT in atomic systems, the plasmonic analogue of EIT or plasmon induced transparency (PIT) has attracted much attention due to its significant advantages and wide practical applications, such as sensor [4,5], active plasmonic switch [6,7], polarization conversion [8], and so on. The realization of PIT is usually achieved by two kinds of schemes: the bright-bright mode coupling [9–14] and bright-dark mode coupling [15–19]. Moreover, several schemes of EIT-like effect have applied two split-ring resonators serving as the bright modes in the microwave [20,21], the THz [22] and optical ranges [23]. The first way is based on the frequency detuning and weak hybridization of two bright modes, while the second one is on the basic of the destructive interference between bright mode and dark mode. For example, Zhang et al. firstly propose a specific design of a nanoplasmonic molecule for the realization of the EIT-like system based on the near-field coupling between bright and dark modes [10]. Liu et al. experimentally demonstrate the plasmonic EIT at the Drude-damping limit using a stacked optical metamaterial consisting of the bright-dark modes [4]. Kekapure et al. propose the analogue of plasmonic EIT at optical frequency in a system of nanoscale plasmonic resonator antennas based on the phase coupling between bright modes [19].

However, most of these structures mentioned above are composed of metallic materials, while those structures exist massive propagation losses with difficulties in controlling the permittivity of the metal, which will result in a low modulation range. It is essential to change their geometrical parameters to realize the dynamic control of the PIT window, but the possibility for massive refabrication is still limited by complex structures and processes, so it is difficult to be used widely available. Recently, many approaches to achieve dynamic tunability of PIT window have emerged which rely on integrating metamaterials with optically active materials such as nonlinear media [24], semiconductors [25], and liquid crystals [26]. As an alternative method, graphene owns many specific optical properties including extreme field confinement and low propagation losses, especially the gate-voltage-dependent feature [27–30]. This feature enables graphene be a new class of plasmonic material to dynamically change the PIT window since its Fermi energy could be tuned by electrostatic gating or chemical doping instead of reconstructing the geometries [31]. Zhao et al. present a design consists of a graphene patch and split-ring that exhibits a sharp induced transparency peak resulting from the destructive interference between two modes [32]. Ding *et.al* propose a structure consists of a graphene layer composed of coupled cut-wire

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pairs printed on a substrate, the PIT window can be observed in a terahertz frequency range due to indirect coupling [33]. Zeng *et.al* demonstrate a graphene metamaterial consists of a series of self-assembled graphene Fabry-Perot cavities [34]. Fu et al. present two parallel-coupled coplanar graphene strips, the weak hybridization between two bright modes with frequency detuning give rise to the original PIT optical response [35].

In this paper, based on the weak hybridization between two bright modes, we design a novel planar plasmonic graphene metamaterial to achieve the PIT effect at terahertz frequencies, which consists of a graphene ring and a graphene strip. Compared to the structures mentioned above, this metamaterial structure is very simple and easy to fabricate experimentally. Also, a higher transmission intensity adjustment from 5 to 95% could be achieved. Both the ring and the strip could be excited by the external field individually, thereby serving as the bright modes. The weak hybridization between two bright modes with the frequency detuning gives rise to the original PIT optical response, and a transparency window is observed when they are placed together. Frequency-shift active control of the PIT resonance is realized by varying the Fermi energy of the graphene without reoptimizing and refabricating the structures, which may offer possible applications as tunable THz functional devices, such as THz switches and modulators. Furthermore, the active control of the group index is highly desired in slow light devices and THz wireless communications.

2. Theoretical model and research method

Fig. 1 shows the structure we designed to demonstrate the PIT phenomenon based on graphene. The basic unit cell of the PIT metamaterial consists of a graphene ring and a graphene strip with a center-to-center space d=3.55 μm. The inner and outer radii of graphene ring are r_1=2 μm and r_2=3.2 μm, respectively. The length and width of the strip are L=9 μm and w=0.7 μm, respectively. The substrate is photopolymer with a relative permittivity of ε=2.4 and a thickness of t=0.5 μm. The structure is arranged along the x and y direction with the same period p=10 μm. The incident wave is perpendicular to the x-y plane with Ex polarization. The numerical calculations are carried out by using the time-domain solver of CST microwave package.

Based on the random-phase-approximation (RPA)[36–38], the surface conductivity of graphene can be described by the Drude model as

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

where E_F represents the Fermi energy of graphene, referenced to Dirac point, ω is the angular frequency, e is the elementary charge, $\hbar$ is the reduced Planck's constant and $\tau = \mu E_F/ev_F^2 \approx 0.5$ps for E_F=0.5 eV is the relaxation time, which matches well with the results reported in the literature. To obtain the value of τ within our simulated spectral window we use mobility $\mu = 10000cm^2\cdot V^{-1}\cdot S^{-1}$ and Fermi velocity $v_F \approx 10^6 m/s$, referenced from experimental results in Ref. [39]. As the charge density could shift the position of Fermi energy [40], accordingly, change the values of relaxation time and DC mobility. Then we can obtain the permittivity of graphene by using the following equation:

$$\varepsilon(\omega) = 1 + i\frac{\sigma_g}{t_g\varepsilon_0\omega}, \tag{2}$$

where ε_0 is the permittivity of vacuum and t_g=*0.5 nm* is the thickness of graphene film. In addition , a monolayer graphene could be obtained by using an optimized liquid precursor chemical vapor deposition method [39]. According to the above permittivity equation of graphene, the different values of permittivity could be calculated by Matlab, and import these dispersion values to the characteristics of the material in order to accomplish the modeling [31].

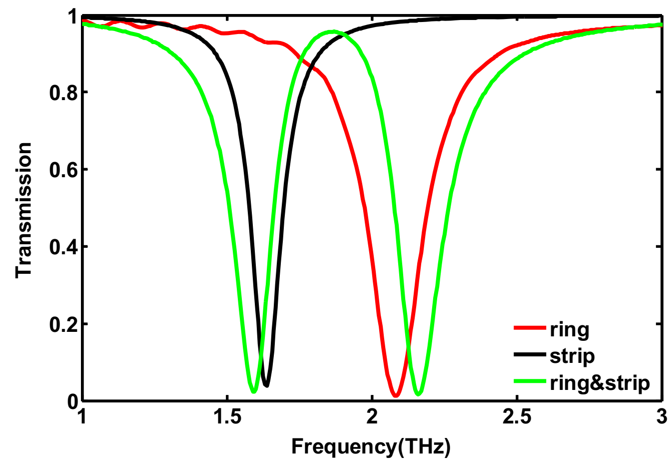

Fig. 2. Transmission spectra of different configurations.(For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

3. Results and discussions

To demonstrate the PIT effect, we numerically calculate the transmission spectra of the unit cell with a graphene ring and a graphene strip, which is indicated by the green line in Fig. 2. The simulated transmission spectrum of the unit cell with the standalone graphene strip is represented by the black line. The simulated transmission spectrum of the unit cell with the standalone graphene ring is demonstrated by the red line. The Fermi energy of 0.50 eV is unchanged in all simulations for Fig. 2. According to Fig. 2, when two elements are combined into a composite structure along the electric field direction, a PIT window with over 95% transmission at 1.86 THz located between two dips at 1.68 THz and 2.14 THz is observed.

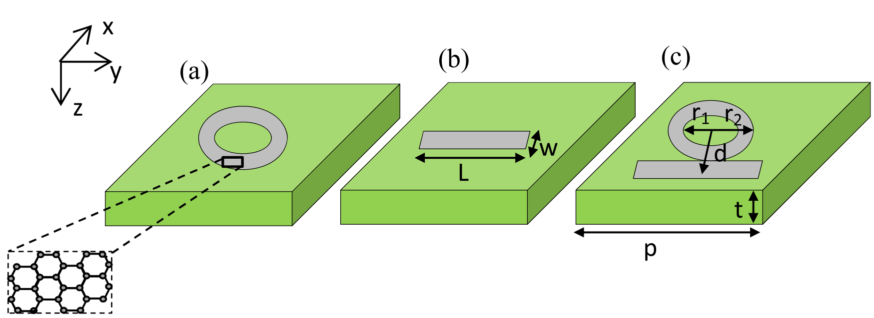

Fig. 1. Schematic view of the unit cell with geometrical parameters. (a) A single graphene ring served as one bright mode. (b) A single graphene strip served as the other bright mode (c) The unit cell of graphene metamaterial. The green region stand for dielectric substrate and grey regions stand for graphene layer.(For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)