Tunable control of electromagnetically induced transparency in hybrid grapheme metamaterials

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Abstract—**We propose a hybrid graphene/metamaterials device based on terahertz frequency. By placing the radiative and dark modes in the vertical and horizontal Si bars, we further demonstrate electromagnetically induced transparency (EIT), analogous to the atomic EIT. We theoretically investigate the strong interaction between graphene and EIT of the metamaterials. By varying the Fermi energy of graphene, the simulations show that graphene can actively modulate the transmission amplitude of EIT. Our results suggest that the demonstrated EIT in hybrid graphene metamaterials may offer new possibilities for applications in terahertz modulators and ultra-sensitive sensors.**

Keywords—Metamaterials; EIT; graphene

I. INTRODUCTION

Electromagnetically induced transparency (EIT) is a quantum interference effect that generates a narrow transparency window with in a broad absorption spectrum[1]. Recently,much interest of researchers focused on the mimic classical EIT phenomenon by using metamaterial at microwave[2], terahertz[3] and optical frequency[4].These investigations have promoted the development of EIT behavior. Many structures have been proposed and demonstrated to realize EIT-like components, such as split ring resonators, dipole antennas, two mutually perpendicular bars.

Graphene is a one-atom-thick material with unique and fantastic optical properties. One of the remarkable properties of graphene is that its conductivity can be dynamically tuned by changing the Fermi energy level that makes graphene an ideal material for realizing optical tunable devices. Recently, the EIT-like effect in graphene-based metamaterials have been proposed[5]. However, these devices are composed of complicatedly patterned graphene-based nano-structure that bring more challenges in fabrication.

II. HYBRID GRAPHENE METAMATERIALS

In this paper, we report on terahertz light modulation via an hybrid graphene/metamaterial device. The simple silicon-based structure is composed of two mutually perpendicular nanoscale bars. The metamaterial defines EIT-like resonance which can be modulated by varying the Fermi energy of which can be modulated by varying the Fermi energy of graphene. The device of hybrid graphene-dielectric, which is composed of the two mutually perpendicular bars designed on the quartz substrate (n = 1.5) by a monolayer of graphene. To the best of our knowledge, this is the first study of the interaction between graphene and mutually perpendicular micrometer scale bars with EIT-like resonance.

In the simulations, graphene is modeled by 2D surface impedance model whose conductivity is simply given by a Drude term $\sigma_{intra} = ie^2E_f /\pi\hbar^2/(\omega + i\tau^{-1})$. The E_f is the Fermi energy. and τ is the intrinsic relaxation time, taken to be 1 ps. Graphene can thus be described effectively by a dielectric function $\varepsilon_g= 1+ i\sigma_{intra} /(\omega t\varepsilon_0)$, where t is the thickness of the ultrathin layer of electron gas, taken to be 1 nm.

The numerical calculation is carried out using the commercial finite difference time domain (FDTD) software package (CST Microwave Studio), and silver is selected as a material due to low intrinsic loss. A frequency-domain solver is used with unit-cell boundary conditions in the x–y plane and Floquet ports in the z axis for terminating the domain.

First, we start by designing the silicon bars without graphene. The thickness of bars is 22um. The terahertz wave with the electric field polarized along the x direction is incident normally to the surface. The vertical bar resonator and horizontal bar resonator is designed respectively. The collective oscillation of the vertical bar resonators are chosen as radiative mode resonance. And the horizontal bar could serve as the dark mode. To demonstrate the EIT-like phenomenon, the sizes of bars is designed to achieve that the transmission dip of vertical and horizontal bars can be overlap.

The schematic of the designed metamaterial is shown in Fig. 1a. Each unit cell comprises two mutually perpendicular silicon bars. Geometric schematic of the unit cell is depicted in Fig. 1b. When planar electromagnetic wave is incident from the positive direction of z-axis with electric field polarizes along x-axis, a strong coupling between the vertical bar and the horizontal bar allows for the excitation of one sharp resonance in the broad resonance profile. In contrast to an atomic EIT system, where the coupling between two energy levels is realized with a pump beam, the coupling between the radiative and dark atoms in the plasmonic EIT system is determined by their spatial separation. It is

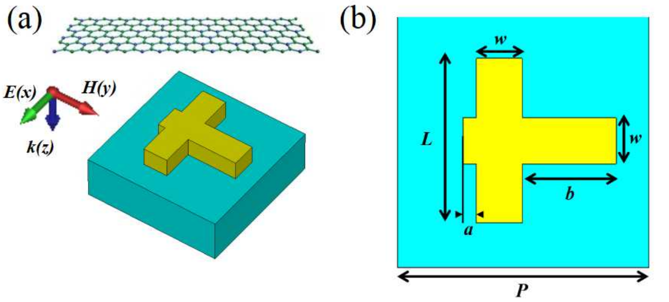

Fig.1(a)Schematic illustration of the proposed dielectric unit cell structure. (b) Top view of the unit cell consisting of two mutually perpendicular silicon-based nanoscale bars .The dimensions are as follows *P*=160μm, *L*=104μm, *w*=29μm, *a*=8μm, *b*=60μm.

important to note that in our EIT-like system asymmetry and spatial location is important in implementing EIT effect [6]. We simulation symmetrical structure such as symmetrical cross structure and T structure, but they can't realize EIT effect.

III. PTUNABLE CONTROL OF GRAPHENE

Fig.2 shows the transmission peak of metamaterial EIT is located at 1.49THz, and the transmission level is as high as 96%. Compared to the resonance frequency of radiative/dark element, slightly frequency shift of EIT peak mainly results from the overlap of middle parts of two mutually perpendicular resonators. The two transmission dips are located at 1.41 and 1.51 THz and the full with at half maximum is 0.073 THz.Therefore, the Q-factor of the transmission peak is 21.

The transmission spectra are simulated to investigate the interaction of graphene with resonance of the EIT-like system. With the graphene, there is a small sharp resonance peak at 1.49 THz in a transmission spectrum, as shown in Fig.3(a). Blueshift of EIT peak in transmission spectrum was happened, and the transmission level is as high as 87%.Optical properties of graphene can be substantially modified via doping or gating since plasmons in graphene depend strongly on the Fermi energy[5,6]. By tuning the Fermi energy, the electron density in graphene is changed, resulting in the change of the resonance frequencies of two mutually perpendicular bars. Therefore, we can dynamically control the EIT spectrum of the graphene structure over a broad range of frequencies. Note that such tunability is accomplish in atomic

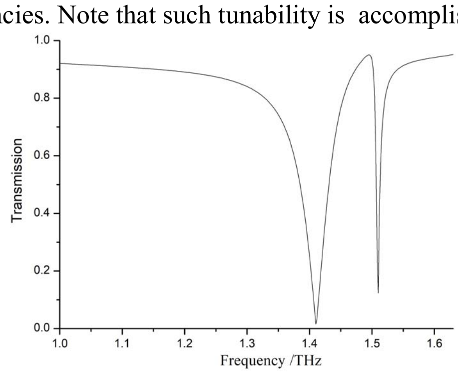

Fig.2 Transmission spectrum of the EIT-like system with graphene

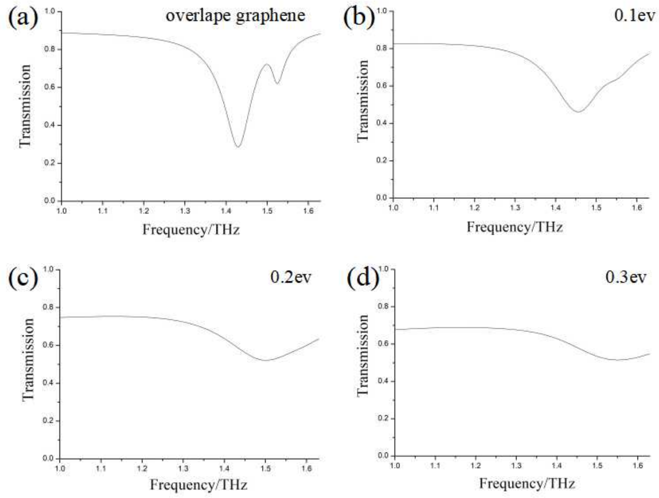

Fig.3(a)-(d) Simulated transmission spectra with a graphene overlayer at different Fermi energy levels,showing the active modulation of the resonance.

or other EIT systems. Fig3(b)-(d) show the transmission spectra for the same graphene EIT structure but at different Fermi energy. We can see that with the decrease of Fermi level, the transmittance becomes smaller and the resonance peak weakens or even disappears. Based on the tuneable transparency windows, switches or modulators can be designed to operate in the investigated frequency regime.

In this paper, we demonstrated the combination of a dielectric metamaterial with a graphene layer could support EIT-like system. Numerical simulation results showed that the transmission of the EIT-like system can be efficiently modulated by varying the Fermi energy when the graphene layer was integrated with the metamaterials. Our next work is to improve the effect of EIT in graphene structure and increase the quality factor.

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REFERENCES

[1] S. Zhang, D. A. Genov, Y. Wang, M. Liu, X. Zhang, “Plasmon-induced transparency in metamaterials”, Physical Review Letters, A101, pp.047401,2008

[2] H. Li, S. Liu, S. Liu, et. al,”Low-loss metamaterial electromagnetically induced transparency based on electric toroidal dipolar response”, Applied Physics Letters, A106, pp.1107, 2015

[3] X. He, L. Wang, J. Wang, et. al, “Electromagnetically induced transparency in planar complementary metamaterial for refractive index sensing applications”, Journal of Physics D Applied Physics, A 46, pp, 365302, 2013

[4] H. Xu, Y. Lu, Y. P. Lee, B. S. Ham,”Studies of electromagnetically induced transparency in metamaterials”, Optics Express, A 18 , pp, 17736-47, 2010

[5] X. Shi, D. Han, Y. Dai, Z. Yu, Y. Sun, “Plasmonic analog of electro-magnetically induced transparency in nanostructure graphene.”, Optics Express, A 21, pp. 28438-43,2013.

[6] Wei, X. Li, N. Zhong, X. Tan, et. al. “Analogue Electromagnetically Induced Transparency Based on Low-loss Metamaterial and its sApplication in Nanosensor and Slow-light Device”, Plasmonics, A 12, pp, 641-647, 2017.