ISSN: 1813-4890

Nonlinear modulation of electromagnetically induced transparency and slow-light effect based on graphene metasurface

Huirong Wang [a], Guanghong Xu, Hao Su, Quan Li

School of Electronic Engineering, Tianjin University of Technology and Education, Tianjin 300222, China;

[a]Sophia1314888@163.com

Abstract

Modeling electromagnetically induced transparency in atomic systems has received a lot of attention through the use of metamaterials. In addition, realizing the active modulation of electromagnetically induced transparent is one of the important research directions, which has potential application value in many fields. In this work, a novel metamaterial is proposed whoes electromagnetically induced transparency effect can be actively modulated in the terahertz band. This metamaterial is composed of graphene and metal structure, and the principle is to achieve nonlinear modulation of electromagnetic induced transparency effects by combining the field-enhancing properties of the metal microstructure with the nonlinear change in the conductivity of graphene at strong-field terahertz. By changing the conductivity of graphene, It can achieve a better modulation effect, and the maximum group delay can reach 5.1ps in the transmission window. The design idea provides a reference for the implementation of compact nonlinear slow light devices.

Keywords

Electromagnetically induced transparency; Graphene; Nonlinear modulation.

1. Introduction

Electromagnetically induced transparency (EIT), a quantum interference effect that occurs in a laser-driven atomic system, can lead to an extremely narrowband transparency window over a wide absorption spectrum[1-3], and the appearance of this phenomenon is always accompanied by extreme changes in dispersion characteristics, which has important application prospects in many aspects, such as slow light, optical switching, and nonlinear enhancement. However, the realization of the quantum EIT effect requires extremely complex experimental conditions, which severely limits its practical application[4]. In recent years, EIT metamaterials based on near-field coupling effects have attracted extensive attention due to their flexible design and easy implementation. The significance is to introduce the original quantum effect into the classical optical category and promote the EIT effect to practical application. Novel active modulation of EIT effect with metamaterials is one of the research hotspots. So far, a variety of active modulation strategies have been proposed[5,6], including graphene-based active modulation strategies.

Graphene is a two-dimensional material with excellent electronic and photonic properties, and one of its most important properties is that the conductivity can be adjusted by means of electronic control and optical doping. Based on this property, good active modulation can be achieved by integrating graphene materials in the metamaterial microstructure. Compared with other strategies that achieve active control through the integration of functional materials, graphene-integrated metamaterial devices are expected to achieve higher modulation speed[7,8].

Researchers have realized the active manipulation of many graphene-based metamaterials by means of external optical pumps, voltages, etc., but so far, most of these designs and experiments have been carried out under the framework of linear action of electromagnetic waves, that is, the response of the outgoing emission is independent of the intensity of the incident electromagnetic wave[9]. It is found that in the terahertz band, when the incident terahertz electric field is strong, the conductivity of graphene will be rapidly adjusted by the incident terahertz electric field, which is also known as the nonlinear effect of graphene[10], which provides a way for the design of active metamaterials with higher modulation speed.

In this paper, we propose a nonlinear EIT control method based on graphene-metal composite metamaterials, in which the metal microstructure is composed of two meanderline resonators (MLRs) and a bar resonator (BR), which can achieve an obvious EIT effect. The graphene material is placed on the upper side of the opening of the MLRs. When the incident terahertz electric field is enhanced, the conductivity of graphene changes, which is mainly caused by the change of the carrier scattering time of graphene, and the change of graphene conductivity affects the resonance of MLRs, which in turn modulates the EIT effect. The intrinsic mechanism of this regulation can be attributed to the modulation of graphene to the resonant damping of MLRs. The results of this study provide a reference for the design of active metamaterials under strong terahermetz incident electric field, and have potential application value in ultrafast teraherz control.

2. Metasurface design

The schematic diagram of the unit structure of the graphene-metal composite EIT metamaterial presented in this paper is shown in Fig. 1, where H(x) represents the terahertz magnetic field direction along x, E(y) represents the terahertz electric field direction along y, and K(z) represents the terahertz vector direction along z. The substrate material is silicon, and the metal structure on it consists of bar resonators (BR) and a pair of meanderline resonators (MLRs) symmetrically located on either side of it. As shown in Fig. 1, the geometric dimensions of the microstructure are: P=100um, L=55um, w=5um, a=40um, b=20um, c=26um, d=17.5um, s=16um, and the thickness of metal and silicon is 200nm and 400um, respectively. The graphene strip is located on the upper side of the MLRs on both sides, and its length extends to the edge of the cell structure on one side and the edge of the bar resonator on the other, with a width of w=5um. In the absence of graphene, the metal structure exhibits a strong EIT effect.

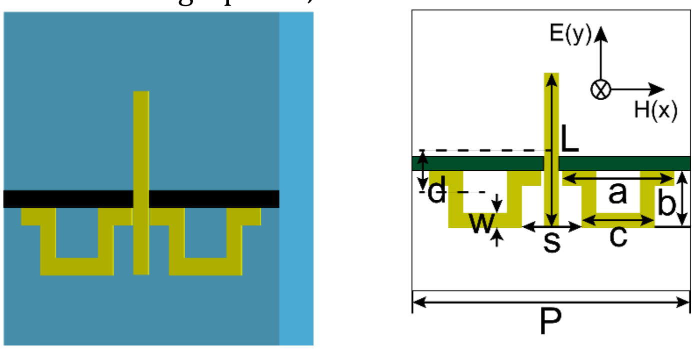

Fig. 1 Schematic diagram of the proposed metamaterial resonator unit cell

In order to study the EIT effect of each part of the metal structure separately, the transmission spectra of BR-only, MLR-only and EIT structures were simulated by using the finite-difference time-domain method (FDTD), and the results are shown in Figs. 2(a)~(c). Using waveguide simulation, the substrate material is set to non-destructive silicon (dielectric constant $\varepsilon = 11.78$), the metallic aluminum is set as a lossy metal with a conductivity of $3.72\times10^{7} S/m$. The terahertz transmission amplitude is defined as $\left|\tilde{t}(\omega)\right| = \left|E_{sam}(\omega)/E_{ref}(\omega)\right|$, where $E_{sam}(\omega)$

and $E_{ref}(\omega)$ are the transmitted coefficients of the simulated terahertz through the metal structure and the blank silicon, respectively, and ω is the angular frequency of the incident terahertz wave. As can be seen from Figs. 2(a) and (b), both the BR and MLRs structures exhibit strong resonance effects at the corresponding resonant frequencies, and the detuning frequencies between the resonant valleys of the BR and MLRs structures are small, and these two resonances are excited by the incident fields polarized in the y- and x-directions, respectively (as shown in the insets in Figs. 2(a) and (b)). The resonant mode of BR has strong radiation loss and therefore a wide resonant bandwidth, while MLRs support a resonant mode with a narrow bandwidth. Based on these resonant characteristics, BR works as the bright mode of the EIT structure, MLRs works as dark modes, and they are placed together in the positions shown in Fig. 1 to form the EIT structure, and the incident polarization is selected as the y-polarization. Although MLRs cannot be directly excited by this incident polarization, they can be indirectly excited by BR through coupling. In the process of interaction, the indirectly excited dark-mode resonance will react to the bright-mode resonance, which interferes with the direct excitation of the incident terahertz wave on the bright-mode, and the coherence is canceled, resulting in the weakening of the bright-mode resonance, and the corresponding change of the transmission spectrum is that the position of the valley of the original open-mode resonance is replaced by a transparent window, that is the EIT effect. As shown in Fig. 2(c), a narrow transparent window can be clearly observed at 0.86 THz.

In order to further understand the causes of the EIT phenomenon, the surface current distributions of BR-only, MLRs-only, and EIT-only structures at the frequency of the resonant valley (or transparent peak) around 0.86THz were simulated, respectively, and the results are shown in Figs. 2(d)~(f). When the two resonators exist separately, it can be observed from Figs. 2(d) and (e) that BR is directly excited by the incident y-polarized terahertz wave, and its surface current is symmetrically distributed in the y-direction, which can be regarded as two symmetrical electric dipole resonances; Under the incidence of x-polarized terahertz waves, the surface currents of the MLRs are distributed in a meanderline shape, that is, they are equivalent to the resonance of two magnetic dipoles, and a large number of different charges can be concentrated at the two ends of their openings, so as to generate a strong local electric field at the openings. When the two resonators form an EIT structure, under the incidence of y-polarized terahertz waves, the BR will be first excited by the external field, and the surface current of its resonance will generate a magnetic field in the z direction, which can pass through the MLRs and thus excite its magnetic dipole resonance. At the same time, an electric field will be generated at both ends of the BR electric dipole in the x-direction, which will also excite the magnetic dipole resonance in the MLRs. The excited MLRs, in turn, have an effect on the resonance of the BR. The end result is that the surface current intensity on the BR is significantly weakened compared to when it was alone, as shown in Fig. 2(f), i.e., the coherence cancellation described above.

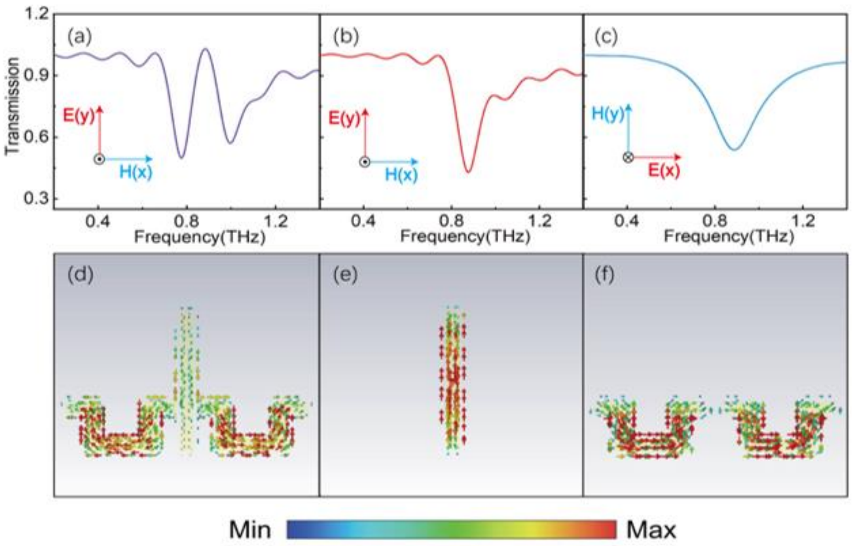

Fig.2 Simulated results without graphene. Simulated amplitude transmission spectra of (a)MLR , (b)MLRs , and (c)EIT structures ; simulated surface current distributions of (d)MLR , (e)SRRs and (f)EIT structures at frequencies at 0.86THz

3. Nonlinear active modulation of EIT

Metamaterial microstructures have a strong enhancement effect on the local near-field, which can enhance the interaction between light and matter at the subwavelength scale, which is of great significance in the design of plasma sensing, modulation, and switching devices. Here the field enhancement effect is combined with the graphene nonlinear effect under the incidence of a strong-field terahertz wave. The graphene strip structure was placed on the upper side of the opening of the MLRs and its resonance was modulated, and then the nonlinear modulation of the graphene-metal composite structure on the EIT effect was studied by numerical simulation. Here, the Kubo model is used to describe the conductivity properties of graphene, which includes both in-band electron-photon scattering and interband electron transition contributions[10].

$$\sigma_g = \sigma_{\text{intra}} + \sigma_{\text{inter}} = i\frac{e^2 k_B T}{\pi\hbar^2(\omega + i\tau^{-1})}\left\{\frac{E_F}{k_B T} + 2\ln\left[\exp\left(-\frac{E_F}{k_B T}\right)+1\right]\right\} + i\frac{e^2}{4\pi\hbar}\ln\left[\frac{2|E_F| - \hbar(\omega + i\tau^{-1})}{2|E_F| + \hbar(\omega + i\tau^{-1})}\right] \quad (1)$$

Here, σ_g is the total conductivity of graphene; e represents the amount of electron charge; k_B stands for Boltzmann's constant; $\hbar$ represents Planck's constant; T stands for temperature; τ represents the carrier scattering time; E_F stands for Fermi level.

According to previous studies, the strong incident wave mainly affects the carrier scattering time τ of graphene, which can induce the redistribution of carriers, and the larger the field strength, the shorter the carrier scattering time[12]. In order to characterize the nonlinear transmission properties of the metamaterial structure, the relevant parameters in the simulation are set according to the nonlinear behavior of graphene in the previous strong-field terahertz system[14]. The Fermi level E_F of graphene is fixed at 0.15 eV, and the carrier scattering time τ is changed from 0.05 ps to 0.2 ps. Fig. 3(a) shows the corresponding simulated transmission results, and it can be seen that with the increase of τ , the transmission spectrum of the EIT changes greatly: the resonance valleys on both sides of the transmission peak gradually weaken, which is manifested by the increase of the transmission coefficient from 0.49 to 0.73 at 0.77 THz and from 0.57 to 0.74 at 0.99 THz, respectively, and the transmission window near 0.86 THz gradually disappears, and the transmission coefficient decreases from 0.99 to 0.67, and the overall resonant behavior gradually decreases towards only BR structure, and there is no obvious resonant frequency shift in the whole process. This change is due to the increase of τ , the conductivity of graphene increases, and the charge at both ends of the opening of MLRs is easier to pass through graphene, which increases its resonance loss and weakens the resonance intensity, and cannot produce sufficient suppression of the resonance of BR, so it eventually leads to the closure of the EIT window.

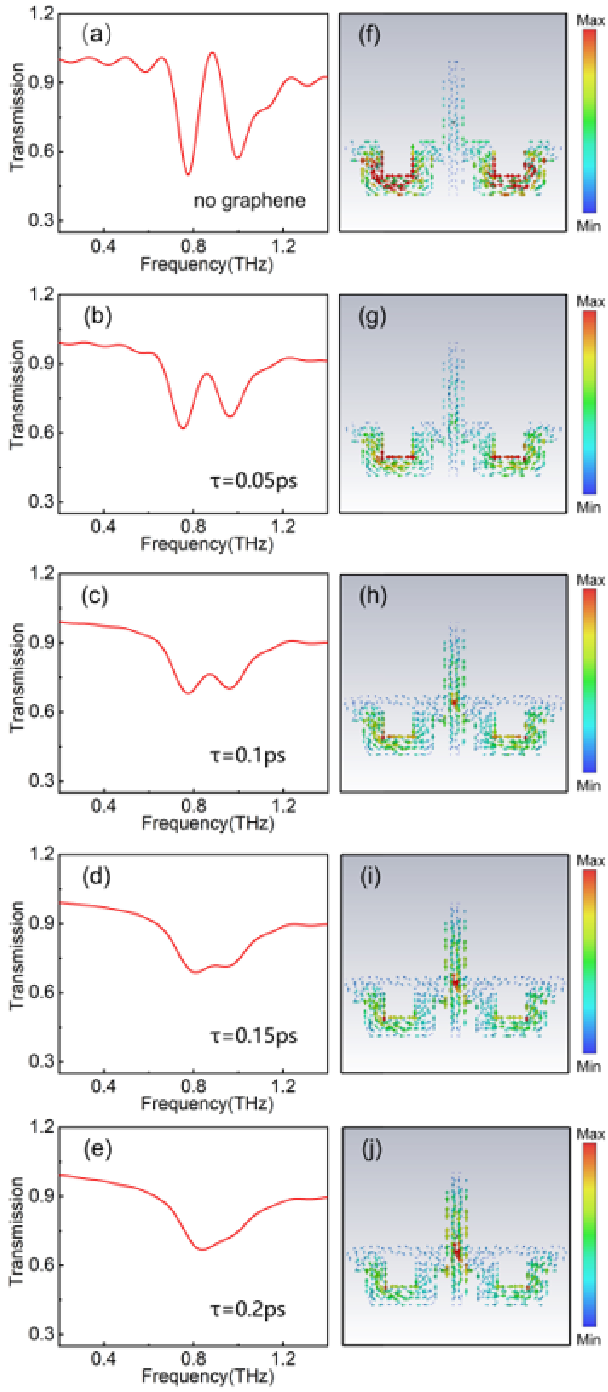

Fig.3. Simulated results of graphene-metal hybrid EIT metamaterial structure at different carrier scattering time. (a)~(e) Simulated transmission spectra;(f)~(g) Simulated surface current distributions.

This modulation phenomenon is also reflected in the distribution of the surface currents shown in Fig. 3. In the absence of a single layer of graphene, the near-field coupling of BR and MLRs produces a strong EIT, and at the transmission window frequency, the resonance intensity of MLRs is stronger, while the resonance intensity of BR is suppressed, as shown in Fig. 3(a). Once graphene is inserted above the opening of MLRs, it has been found from previous studies that graphene at static mainly exhibits a semi-metallic effect, and the opening of MLRs is turned on to a certain extent. With the gradual increase of graphene scattering time τ , the field strength of the corresponding actual incident electromagnetic wave decreases [15], the conductivity of graphene increases, and the recombination effect of positive and negative charges at both ends of the opening is also enhanced, so the charge density in the opening of MLRs gradually decreases, the surface current weakens, and the resonance gradually weakens.

In addition to this, in the field of slow light, the EIT phenomenon cannot be ignored because it retains more photons by greatly reducing the speed of light in the medium. The performance of the slow-light effect can be expressed in terms of group delay (τ_g), defined as:

$$\tau_g = \frac{d\theta}{d\omega} \tag{2}$$

The proposed structure shows the group delay during the change of carrier scattering time from 0.05 ps to 0.2 ps, as shown in Fig. 4, at 0.86 THz, the group delay reaches a maximum of 5.1 ps when the carrier scattering time is 0.05 ps.

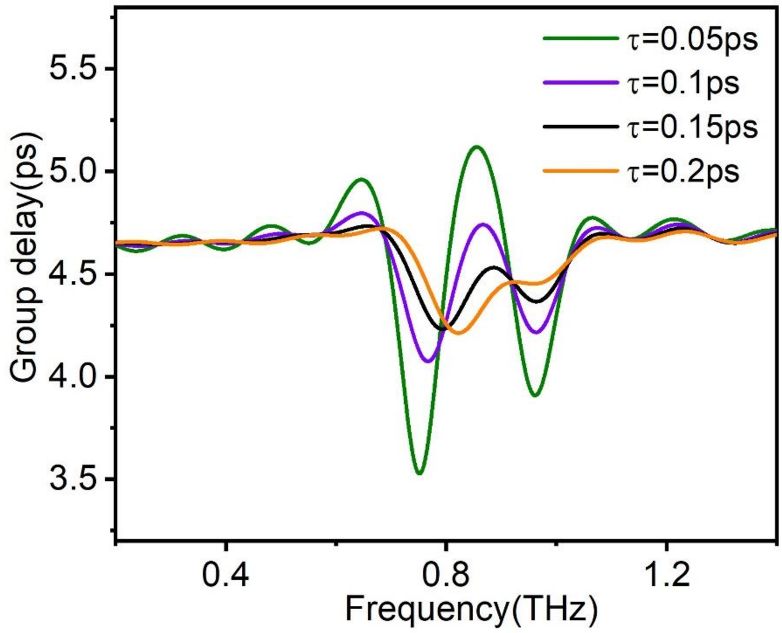

Fig.4. The delay time of the metamaterial varies with the frequency at different carrier scattering time

4. Conclusion

In this paper, the EIT effect in composite metamaterial structures composed of graphene and metals in the terahertz band is investigated. By combining the field enhancement effect at the opening of MLRs and the nonlinear effect of the change of graphene's conductivity under a strong terahertz electric field, the transmitted amplitude of the EIT window is effectively controlled by the intensity of the incident terahertz field, and the nonlinear active modulation of the EIT effect is realized. The intrinsic mechanism of its modulation can be attributed to the modulation of the resonant damping rate of MLRs by graphene. Finally, the corresponding group delay with the frequency of the incident terahertz wave under different carrier scattering times is obtained, and intrinsic silicon can be used as the substrate in future experiments to avoid silicon being excited by strong-field terahertz waves and destroying the modulation effect [17]. This structure has application potential in the fields of high-speed slow light modulation and optical switching, and provides a new way to realize high-speed active control devices.

References

[1] Singh, R., I. Al-Naib, et al. The Fano resonance in symmetry broken terahertz metamaterials, IEEE Transactions on Terahertz Science & Technology. Vol. 3 (2013) No.6, p.820–826.

[2] Liu X, Gu J, et al. Electromagnetically induced transparency in terahertz plasmonic metamaterials via dual excitation pathways of the dark mode, Applied Physics Letters. Vol. 100 (2012) No.13, p.36–41.

[3] Nakanishi, T., et al. Storage of electromagnetic waves in a metamaterial that mimics electromagnetically induced transparency, Physical Review B. Vol. 87 (2013) No.16, p.1110.

[4] Shuang Z, Genov D A, et al. Plasmon-induced transparency in metamaterials[J]. Physical Review Letters, 2008, 101(4):218-22.

[5] Zhou J H, Zhang C X, et al. Controllable all-optical modulation speed in hybrid silicon-germanium devices utilizing the electromagnetically induced transparency effect[J]. Nanophotonics, 2020, 9(9):2797-2807.

[6] Zhang M, Yan F P, et al. Design and analysis of electromagnetically induced transparency in THz multiband[J]. Chinese Journal of Lasers, 2021, 48(3):0314001.

[7] Lee S H, Choi M, et al. Switching terahertz waves with gate-controlled active graphene metamaterials[J]. Nature Materials, 2012, 11(11):936-941.

[8] Zhou Y X, Huang Y Y, et al. Terahertz properties of graphene and graphene-based terahertz devices[J]. Chinese Journal of Lasers, 2019, 46(6):0614011.

[9] Kindness S J, Almond N W, et al. Active control of electromagnetically induced transparency in a terahertz metamaterial array with graphene for continuous resonance frequency tuning[J]. Advanced Optical Materials, 2018, 6(21):1800570.

[10] Li Q, Wang S, et al. Nonlinear modulation of plasmonic resonances in graphene-integrated triangular dimers at terahertz freguencies [J]. Materials, 2019, 12(15):2466-2476.

[11] Zhang Y B, Tan Y W, et al. Experimental observation of the quantum Hall effect and Berry's phase in graphene[J]. Nature, 2005, 438(7065):201-204.

[12] Zhang J, Zhu Z H, et al. Towards photodetection with high efficiency and tunable spectral selectivity:graphene plasmonics for light trapping and absorption engineering[J]. Nanoscale, 2015, 7(32):13530-13536.

[13] Hafez H A, Lévesque P L, et al. Intense terahertz field effects on photoexcited carrier dynamics in gated graphene[J]. Applied Physics Letters, 2015, 107(25):251903.

[14] Hwang H Y, Brandt N C, et al. Nonlinear THz conductivity dynamics in P-type CVD-grown graphenelJ]. The Journal of Physical Chemistry B, 2013, 117(49):15819-15824.

[15] Li S X, Nugraha P S, et al. Terahertz electric field modulated mode coupling in graphene-metal hybrid metamaterials[J]. 0ptics Express, 2019， 27(3):2317-2326.

[16] Liu N, Langguth L, et al. Plasmonic analogue of electromagnetically induced transparency at the drude damping limit[J]. Nature Materials, 2009, 8(9)758-762.

[17] 0vchinnikov A V, Chefonov O V, et al. Second harmonic generation in the bulk of silicon induced by an electric field of a high power terahertz pulse[J]. Scientific Reports, 2019， 9:9753.

[18] Tarekegne A T, Iwaszczuk K, et al. Impact ionization in high resistivity silicon induced by an intense terahertz field enhanced by an antenna array[J]. New Journal of Physics, 2015， 17(4):043002.