Active control of the electromagnetically induced transparency (EIT) is highly desirable for advanced terahertz (THz) device applications. Currently, the EIT peak positions in the graphene-based metamaterials have been actively controlled by tailoring Fermi energy of graphene via electric doping. However, there is still a considerable challenge to realize active strength modulation of the EIT peak without frequency shifting. Here, a hybrid metal-graphene structure, consisting of the metal-based EIT metamaterial and patterning graphenes, is proposed at the THz frequencies. Through changing Fermi energy of graphene, the EIT peak strength can exhibit both active modulation and on-to-off switch without frequency shifting. Moreover, theoretical model and field distributions discover that the active response can be attributed to the increasing damping rate of the dark mode caused by the controllable conductivity of graphene. In addition, the controllable group delay is also achieved for the slow light applications. Therefore, this work provides the possibility for designing compact slow light devices in the information processing and telecommunication applications.

1. Introduction

Recently, graphene, obtained from graphite by mechanical exfoliation method, is considered as the next generation promising optoelectronic material due to unique physic properties [1]. Compared with the traditional metal, the conductivity of graphene can be actively tailored by doping, which can provide an attractive platform for tunable metamaterials (MMs) [2]. Currently, various EIT MMs obtaining by patterning or stacking graphene structures have been widely investigated [3–6]. Among the reported graphene-based EIT MMs, however, only the EIT resonance frequency can be actively tuned by adjusting Fermi energy of graphene via electrostatic doping. Moreover, the corresponding frequency modulation depth (MD) is very low due to weak coupling with the incident wave [7].

In practical applications, it is highly desirable for actively controlled resonance strength of the transparency peak without frequency shifting, and it is more suitable for compact slow light devices and modulators [8]. To actively control the EIT resonance strength, currently, different hybrid EIT MMs have been proposed and demonstrated by integrating various active materials or MEMS technologies, such as semiconductors [9, 10], organic-inorganic hybrid perovskites [11], two dimensional transition metal dichalcogenide materials [12, 13], phase change materials [14, 15], graphene [8], and MEMS structures [16, 17]. Specially, the hybrid metal-graphene EIT MMs have attracted great interest in the terahertz range due to its easy excitations and fabrications [18–21]. Inspired by our previous metal- and graphene-based metamaterials [22, 23], here we propose a hybrid metal-graphene metamaterial to realize actively intensity modulation of the transparency peak without frequency shifting. Moreover, the coupled model and field distributions disclose that this active response arises from the tunable conductivity of graphene patterned under the split gap of the dark mode resonator. In addition,
the corresponding group delay can also exhibit active response. Therefore, this work opens up a new possibility for designing active terahertz devices in the future information process and communication applications.

2. Designs and simulations

Figure 1 shows the schematic of the proposed hybrid EIT metamaterial, in which unit cell structure of the EIT metamaterial is consisted of two metallic split ring resonators (SRRs) connecting by a 90°-twisted form each other, and the vertical SRR (VSRR) structure and horizontal SRR (HSRR) structure act respectively as the bright and dark resonators, as shown in figure 1(b). A notable EIT window is obtained through tailoring the near field coupling between bright–dark modes. To dynamically control the amplitude of the EIT window, the single layer graphene are deposited and patterned under the split gap of the HSRR structures. To handily dope graphene, in addition, the HSRR structures are mutually connected by metal ribbon to create the top gate, as displayed in figure 1(c). Thus, the near field coupling between two resonators can be actively tuned through shifting Fermi energy of graphene via electric doping, consequently, manipulating dynamically resonance strength of the EIT window.

To verify our designed functions, the resonance behaviors of the transparency window are calculated by the finite difference time domain (FDTD) method, in which the x- and y-directions are set as unit cell respectively and the z-direction is set as perfectly matched layer. The incident wave polarizing along the y-direction illuminates normally the metamaterial surface, as shown in figure 1(a). In the calculations, the structural parameters are as follows: \( p_x = p_y = 150 \mu m, l = 52 \mu m, w_1 = 5 \mu m, w_2 = 12 \mu m, w_3 = 10 \mu m, g = 10.8 \mu m, d = 1 \mu m, \) and \( h = 20 \mu m. \) The DC conductivity and thickness of lossy metal are \( 3.56 \times 10^5 \) S/m and 0.2 respectively. The relative permittivity and thickness of the lossless silicon are 11.7 and 300 \( \mu m \) respectively, and that of the SiO\(_2\) layer are 3.9 and 30 nm, while the permittivity of the graphene \( \varepsilon_g \) is given by the following expression [24]

\[
\varepsilon_g = 1 + \frac{\sigma_g(\omega)}{\omega\varepsilon_0 \mu_g} \tag{1}
\]

where \( \omega \) and \( \mu_g \) are the angular frequency and thickness of the monolayer graphene respectively, and \( \varepsilon_0 \) is the permittivity of vacuum. The conductivity of graphene \( \sigma_g \) can express as [25]:

\[
\sigma = -\frac{e^2 k_B T}{\pi h^2 (\omega - j2f)} \left( \frac{E_F}{k_B T} + 2 \ln \left( e^{-E_F/k_B T} + 1 \right) \right) \tag{2}
\]

here, \( e \) is the charge of an electron, \( h = h/2\pi \) is the reduced Planck’s constant, \( k_B \) is Boltzmann’s constant, \( T \) is the Kelvin temperature, and \( E_F \) is the Fermi energy of graphene, \( \Gamma = \tau^{-1} \) is the phenomenological scattering rate, and \( \tau \) is the carrier relaxation time described by \( \tau = (\mu E_F)/(eF^2) \), in which \( \mu = 3000 \) cm\(^2\)/V \( \cdot \) s and \( v_F = 1.1 \times 10^6 \) m/s are employed in our calculations [26]. According to equation (2), the conductivity of graphene can be actively tuned by shifting Fermi energy. Meanwhile, the Fermi energy of graphene can be dynamically controlled by gate voltage (as shown in figure 1(c)) [27, 28]:

\[
E_F = h v_F \sqrt{\pi \varepsilon_0 \varepsilon_r V_g / \varepsilon d_i} \tag{3}
\]
Here, $\varepsilon_r$ is the relative permittivity of SiO$_2$, and $d_s$ is the thickness of SiO$_2$ layer. As a result, by tuning the conductivity of graphene through the gate voltage $V_g$, the interaction between incident waves and the hybrid structure could be effectively controlled.

### 3. Results and discussions

To figure out the formation process of the transparency window, the transmission spectra of three different metallic metamaterial structures, including the isolated VSRR array, isolated HSRR array and their combining structure, are calculated respectively and the corresponding calculated results are presented in figure 2. For the incident light polarizing along y-direction, the isolated VSRR structure exhibits a clear resonance dip around 0.6 THz due to direct excitation (as depicted by the pink curve), whereas the HSRR structure is inactive in the whole interesting frequency range (as depicted by the blue curve). Thus, the VSRR and HSRR can respectively serve as the bright and dark modes. When both resonators are together gathered within a unit cell, however, a notable transparency window is induced around 0.6 THz due to destructive interference caused by the near field coupling between two resonators (as depicted by the red curve), which is the typical EIT-like feature observed in previous report [29].

To understand the forming mechanism of the transparency window, the surface currents and electric field distributions are calculated respectively. Figure 3 displays the field distribution results at the resonance dip and transparency peak. For the individual VSRR structure, the surface currents at the resonance dip exhibit the circulating distributions, while the electric fields are strongly confined in the split gap, as shown in figures 3(a) and (b). This feature is the typical field distributions of LC resonance, which further confirms that the VSRR is bright mode. For the combined structure, the surface currents and electric fields at the transparency peak are strongly confined on the surface of the HSRR and in the split gap of the HSRR owing to near field coupling between bright and dark modes, whereas the fields of the VSRR are completely restrained compared with that of the individual VSRR, as presented in figures 3(c) and (d). that is, the obvious energy transfer from the VSRR to HSRR structures occurs at the transparency peak via near field coupling, indicating that indirect excitation of the HSRR. Consequently, the destructive interference originating from the near field coupling between two structures induces a sharp transparency window.

Next, we discuss and analyze the dynamic characteristic of the transparency window by tailoring Fermi energy of graphene via electric doping and the corresponding response results are shown in figure 4. As observed in figure 4(a), as Fermi energy of graphene changes, the amplitude of the transparency window shows the active modulation without frequency shifting. For example, in absence of graphene, the metallic EIT metamaterial has a notable transparency peak with a amplitude of 90% around 0.6 THz. Once the EIT structure marries with graphene to establish hybrid structure, slight decrease in the strength of the transparency peak is observed due to the intrinsic conductivity of graphene (no shown here) [30]. As increasing Fermi energy from 0.1 to 0.55 eV, moreover, it is clearly noted that the transparency peak amplitude gradually reduces from 64.3% to 29.5% due to increase in the conductivity of graphene. When Fermi energy is further increased up to 1.0 eV, the transparency window is totally annihilated and a single broad LC resonance dip with the transmission of 20.6% appears around 0.6 THz. As a result, the transparency peak can realize on-to-off switching without frequency shifting through tuning Fermi energy of graphene. To quantify the modulation capacity of this hybrid structure, the transparency peak strength as a function of Fermi energy is further plotted in figure 4(b). It is clearly observed that
the transparency peak strength exhibits an exponential decrease with increase in Fermi energy of graphene, obtaining the amplitude modulation depth of 77%. Therefore, these results demonstrate that the hybrid structure can active intensity modulation of the transparency peak by changing Fermi energy of graphene.

Figure 3. Surface currents and electric field distributions of different structures at the resonance dip and the transparency peak: (a) surface currents and (b) electric fields in isolated VSRRs, (c) surface currents and (d) electric fields in metal-based EIT structure.

Figure 4. (a) Simulated transmission spectra of the hybrid EIT metamaterial with different Fermi energy, and (b) transparency peak as a function of Fermi energy.
To expressly elucidate the physic mechanism of the active modulation behavior, a classical oscillator coupled model is employed to investigate the coupling effect between two resonators in the hybrid metamaterial. In this model, the bright VSRR excited directly by the incident field $E(t)$ is represented by oscillator 1 and the dark HSRR excited indirectly by near field coupling is represented by oscillator 2. Thus, the coupling effect between two oscillators can be expressed by the coupled differential equations as follows:

$$\ddot{x}_1(t) + \gamma_1 x_1(t) + \omega_0^2 x_1(t) + \kappa E = \lambda E$$  \hspace{1cm} (4)

$$\ddot{x}_2(t) + \gamma_2 x_2(t) + (\omega_0 + \delta)^2 x_2(t) + \kappa x_1(t) = 0$$  \hspace{1cm} (5)

Here, $x_1(t), x_2(t), \gamma_1$ and $\gamma_2$ are resonance intensities and damping factors of the bright and dark resonators, respectively, $\omega_0$ is the resonance frequency of the bright resonator before coupling with the dark resonator, $\delta$ is the detuning of the resonance frequency of the dark resonator from the bright resonator, $\kappa$ denotes the coupling coefficient between two resonators, and $\lambda$ is a geometric parameter indicating the coupling strength of the bright resonator with the incident field $E$. After solving the equations (4) and (5) with the approximation $\omega - \omega_0 \ll \omega_0$, the susceptibility $\chi$ of the hybrid metamaterial as the function of frequency can be expressed as follows:

$$\chi = \chi_r + i\chi_i \propto \frac{(\omega - \omega_0 - \delta) + \frac{i\gamma_2}{2}}{(\omega - \omega_0 + \frac{i\gamma_2}{2})(\omega - \omega_0 - \delta + \frac{i\gamma_2}{2}) - \frac{\kappa^2}{4}}$$  \hspace{1cm} (6)

Since the power loss of the hybrid metamaterial is in proportion to the imaginary part of the susceptibility, thus the transmission $T$ can be extracted from $T = 1 - \lambda \chi_i$. The theoretically fitted and numerically calculated transmission spectra for different Fermi energies of graphene are displayed in figure 5, in which two transmission spectra exhibit very excellent agreement except for slight deviations arising from the periodical effect of the metamaterials [32]. In addition, the corresponding fitting parameters $\gamma_1, \gamma_2, \kappa$ and $\delta$ as the function of Fermi energy are also extracted and plotted in figure 6. It is obviously observed from figure 6 that as increase in Fermi energy, the $\gamma_1, \kappa$, and $\delta$ remain almost unchanged, whereas the amplitude of $\gamma_2$ increases by an order of magnitude from 0.01 to 0.83 THz. Thus, it can be inferred that the active control of the transparency peak intensity is ascribed to the increase in the damping rate $\gamma_2$. For the hybrid structure, therefore, the patterned graphene integrated into the split gap of the HSRR structures behaves as a metal structure, which can shorten two ends of each split gap with the high conductivity. As the Fermi energy of graphene increases, the increasing $\gamma_2$ begins to gradually hamper the destructive interference between the bright and dark modes, leading to decrease in the resonance strength of the dark resonator. when the Fermi energy of graphene is 1.0 eV, the damping rate $\gamma_2$ become too large to support the excitation of the dark mode, eventually resulting in the full vanishment of the transparency peak.

To better understand the degradation behavior of the dark mode, it was necessary to discuss electric field distributions at the transparency peak frequency under different Fermi energies. Field distributions at three different Fermi energy states (no graphene, $E_F = 0.55$ eV, and $E_F = 1.0$ eV), corresponding respectively to sharp
EIT peak, invisible EIT peak and only LC resonance, are presented in figure 7. As observed in figure 7(a), in the absence of graphene, the electric fields are strongly confined in the split gaps of the dark HSRRs, and the bright VSRRs are completely restrained, which is the typical field distributions of the EIT-like effect [4]. Once doping graphene, however, the conductivity increases due to carrier accumulations, leading to the redistributions of the
electric fields, in which the HSRRs and VSRRs are synchronously excited at $E_F = 0.55$ eV and but the dark HSRRs is partly hampered comparing with that of no graphene, as shown in figure 7(b). As further increasing Fermi energy up to 1.0 eV, the conductivity become large enough to shortens the split gaps of the HSRRs, forming the close rings. As a result, the HSRRs are completely suppressed and the electric field distributions of the VSRRs restores again to that of the isolated VSRRs (as observed in figure 7(c)), here, the dark mode excitation is fully restrained and the transparency window is switched off. Obviously, the origin of the transparency peak modulation essentially arises from the tunable conductivity of graphene obtained via doping.

Figure 8(a) shows the transmission phase spectra for different Fermi energies. As expected, the transmission phase exhibits dramatic change with the increase of Fermi energy, indicating that the slow-light effect can be actively tuned. To characterize slow-light effect, group delay ($\tau_g = -d\phi(\omega)/d\omega$, in which $\phi(\omega)$ and $\omega$ are the phase shift and angular frequency of the transmission, respectively) is employed to quantize the speed of the incident wave passing through the sample [34]. As observed in figures 8(b) and (c), the group delay within the transparency window experiences a dynamic modulation as Fermi energy increases. For example, without graphene, the transmission phase shift shows a steepest phase jump within the transparency window, producing a maximum group delay of $\tau_g = 11.4$ ps, which corresponds to the 3.42 mm distance of free space propagation. Subsequently, as the Fermi energy increases from 0.1 eV to 0.55 eV, the group delay exhibits a dramatic decline and tends to a negative value. As further increasing to 1.0 eV, the group delay is switched into a typical LC resonance feature. Here, the slow light characteristic completely disappears. Thus, an actively controlled group delay is obtained by shifting Fermi energy. In addition, the group delay peak as the function of Fermi energy is also plotted in figure 8(d) to further analyze the modulation effects of the slow light. As seen in figure 8(d), the group delay peak exhibits the nonlinear decline as Fermi energy increases. Therefore, the hybrid structure has excellent performance with active and switchable slow light by changing Fermi energy, which is greatly advantage to the development of multifunctional devices.
4. Conclusions

In this paper, a hybrid EIT metamaterial, composed of two coupled split ring resonators connecting mutually by a 90°-twisted form and the patterning graphenes, has been designed and analyzed. The numerical results demonstrate that though tuning Fermi energy of graphene, the transparency peak can realize active modulation and on-to-off switching without frequency shifting. Theoretical analysis and field distributions reveal that the active control behavior originates from the tunable conductivity of graphene caused by electrostatic doping. In addition, an actively tunable and switchable group delay is also demonstrated. Therefore, the proposed hybrid EIT metamaterial opens up new avenue for design and realization of highly compact terahertz functional devices in signal processing applications.

Acknowledgments

The work is supported by the National Natural Science Foundation of China (62075052 and 51672062), Science Foundation of the National Key Laboratory of Science and Technology on Advanced Composites in Special Environments (JCKYS2020603(C09), Natural Science Foundation of Heilongjiang Province (LH2019F022), and Project of Innovative and Entrepreneurship Training Program for College students in Heilongjiang Province (201810214105).

ORCID iDs

Xiaoming Xu © https://orcid.org/0000-0002-4784-3289
Xunjun He © https://orcid.org/0000-0002-5597-4289

References

[1] Gori P, Pulci O, Vallaro R D L and Guattari C 2014 Energy Procedia 45 512
[2] Bokdam M, Khomyakov P A, Brooks G, Zhong Z and Kelly P J 2011 Nano Lett. 11 4631
[3] Sun C, Si N, Dong Z W and Deng X X 2016 Opt. Express 24 11466–74
[4] He X J, Yang X Y, Lu G J, Yang W L, Wu F M, Yu Z G and Jiang J X 2017 Carbon 123 668–75
[5] Wang Y, Tao M N, Pei Z, Yu X Z, Wang B H, Jiang J X and He X J 2018 RSC Adv. 8 37057–63
[6] Gao E D, Liu Z M, Li H J, Xu H, Zhang Z B, Luo X, Xiong C X, Liu C, Zhang B H and Zhou F Q 2019 Opt. Express 27 13884–94
[7] Jia W, Ren P W, Jia Y L and Fan C Z 2019 Phys. Chem. C 123 18560–4
[8] Chen M M, Xiao Z Y, Lu X J, Lv F and Zhou Y J 2020 Carbon 159 273–82
[9] Gu J Q et al 2012 Nature Communications 3 1151
[10] Hu Y Z, Jiang T, Sun H, Tong M Y, You J, Zheng X, Xu Z J and Cheng X G 2020 Laser Photonics Rev. 1900338
[11] Zhou H J et al 2019 Photons Research 7 994
[12] Ji J, Zhou S Y, Wang W J, Ling F R and Yao J Q 2019 Nanoscale 11 9429–35
[13] Hu Y Z et al 2020 Nano Energy 68 104280
[14] Abdollahramezani S, Hemmatyar O, Taghinejad H, Krasnok A, Kiarnashnejad Y, Zandehshahvar M, Ali A and Adibi A 2020 Nanophotonics 9 1189–241
[15] Zhang Z J, Yang J B, Han Y X, He X, Zhang J J, Huang J, Chen D B, Xu S Y and Xie, W L 2020 Appl. Phys. A 126 199
[16] Huang Y, Nakamura K, Takida Y, Minamida H, Hane K and Kanamori, Y 2020 Scientific Reports 10 20807
[17] He X J, Ma Q X, Jia P, Wang L, Li T Y, Wu F M and Jiang J X 2015 Integr. Ferroelectr. 161 85–91
[18] Yan X C, Wang T, Xiao S Y, Liu T T, Hou H W, Cheng J J and Jiang X Y 2017 Sci. Rep. 7 13917
[19] Liu T T, Yi Z and Xiao S Y 2017 IEEE Photonics Technol. Lett. 29 1998–2000
[20] Xiao S Y, Wang T, Liu T T, Yan X C, Li Z and Xu C 2018 Carbon 126 271–8
[21] Liu C X, Liu P G, Yang C, Lin Y and Zha S 2018 Opt. Mater. Express 8 1132–42
[22] Pitchappa P, Manijappa M, Ho C P, Qian Y, Singh R, Singh N and Lee C K 2016 Appl. Phys. Lett. 108 111102
[23] He X J, Huang Y M, Yang X Y, Zhu L, Wu F M and Jiang J X 2017 RSC Adv. 7 40321
[24] Kajipa C S R, Yakovlev A B, Hanson G W and Padooru Y R 2012 Phys. Rev. B 85 245407
[25] Hanson G W 2008 J. Appl. Phys. 103 064302
[26] Inawali G, Rao Y, Yan H and Heinz T F 2013 Nano Lett. 13 524
[27] Novoselov K S, Geim A K, Morozov S V, Jiang D, Zhang Y and Dubonos S V 2004 Science 306 666–9
[28] Valmorra F et al 2013 Nano Lett. 13 3193–8
[29] Singh R, Rockstuhl C, Lederer F and Zhang W L 2009 Physical Review B 79 085111
[30] Srivastava Y K, Chaturvedi A, Manijappa M, Kumar A, Dayal G, Kloc C and Singh R 2017 Adv. Optical Mater. 3 11700762
[31] Liu N, Languth L, Weiss T, Kastel J, Fleischhauer M, Pfau T and Giessen H 2009 Nat. Mater. 8 758–62
[32] Koschyn T, Marko P, Economou E N, Smith D R, Vier D C and Sokolows C M 2005 Phys. Rev. B 71 1245105
[33] Yabuuchi R, Burrow J A, Melkonian S M, Sarangan A, Mathews J, Agha I and Stearles T A 2018 Physical Review B 97 155403
[34] Yang X, Yu M, Kwong D L and Wong C W 2009 Phys. Rev. Lett. 102 173902