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# Tunable Plasmon-Induced Transparency through Bright Mode Resonator in a Metal–Graphene Terahertz Metamaterial

# Guanqi Wang<sup>D</sup>, Xianbin Zhang \* and Xuyan Wei

Department of Applied Physics, Xi'an University of Technology, Xi'an 710048, China; gqwang@stu.xaut.edu.cn (G.W.); weixuyan113@stu.xaut.edu.cn (X.W.)

\* Correspondence: zhangxianbin@xaut.edu.cn; Tel.: +86-29-8206-6351

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**Abstract:** The combination of graphene and metamaterials is the ideal route to achieve active control of the electromagnetic wave in the terahertz (THz) regime. Here, the tunable plasmon-induced transparency (PIT) metamaterial, integrating metal resonators with tunable graphene, is numerically investigated at THz frequencies. By varying the Fermi energy of graphene, the reconfigurable coupling condition is actively modulated and continuous manipulation of the metamaterial resonance intensity is achieved. In this device structure, monolayer graphene operates as a tunable conductive film which yields actively controlled PIT behavior and the accompanied group delay. This device concept provides theoretical guidance to design compact terahertz modulation devices.

Keywords: plasmon-induced transparency; metamaterial; graphene; bright mode

## 1. Introduction

The coupling of plasma response in metamaterials can mimic an electromagnetically induced transparency (EIT) effect, the physical mechanism of which is explained by plasma resonance, so it is called plasmon induced transparency (PIT) [1–3]. In the terahertz (THz) regime, the electromagnetic properties accompanying PIT effect, such as wave velocity delay and high refractive index sensitivity, mean that PIT metamaterials can be effectively used in a terahertz buffer [4] and refractive index sensor [5]. However, it is worth noting that most of these devices are passive, and people expect to realize more active and controllable terahertz PIT devices on this basis. In recent years, controlled active mediums, integrated into resonator structures, are reported for the active modulation of PIT metamaterials [6–9]. Currently, graphene, as a novel active material, has attracted extensive attention of researchers.

As a typical representative of two-dimensional materials, graphene has been widely studied in many fields, such as physics, chemistry, energy, and materials, thanks to its unique mechanical, thermal, and electromagnetic properties [10,11]. In the terahertz band, the conductivity of graphene depends on the intraband transition. By moving the Fermi energy through electrostatic gating and chemical doping, the conductivity of graphene can be changed, and then its electromagnetic response to terahertz wave can be adjusted flexibly. Based on the remarkable tunability of graphene conductivity in the terahertz band, many terahertz control devices are proposed with graphene as the active material [12–16]. The combination of graphene and metallic metamaterials, and the design of metamaterials based on a patterned graphene structure can be the basis of the construction of tunable PIT metamaterials [17–23]. However, it is difficult to tune the surface conductivity of patterned graphene resonators, which limits the scalability of these tunable approaches in practical application.

In this article, an active control of the PIT resonance in a terahertz hybrid metal-graphene metamaterial is proposed. The hybrid PIT metamaterial consists of a pair of classic split-ring resonators

(SRRs) array, in which an unpatterned graphene ribbon is laid directly under the bright element of the metallic metamaterial. By manipulating the electromagnetic response of the bright mode resonator via shifting the Fermi energy of graphene, the tunable PIT behavior can be obtained in the hybrid structure. The main advantage over the common dark mode control scheme is more spectrum range for actively controlling the terahertz waves, which is modulated by the two resonance dips beside the transparency peak. Thus, this work has opened up a new avenue for designing ultrafast real-time control functional devices in terahertz regime.

#### 2. Proposed Structure and Simulation Method

A representative unit cell of the proposed metamaterial, based on two orthogonally twisted SRRs, is vividly illustrated in Figure 1. The meta-atoms unit are made of aluminum (Al), with  $t_{Al} = 200$  nm being the thickness, and a silicon (with refractive index 3.42) substrate is assembled at the bottom. The proposed concept of a metal–graphene metamaterial can be realized by the different types of structures, but in this paper, this simple SRR structure is selected due to the perfect electrical interplay between its split-gap and the active graphene layer material [18,24]. The linearly y-polarized plane wave along the negative z direction is adopted as incident light all through the paper. The right and left SRRs are termed as SRR1 and SRR2, respectively. The SRR1, acting as the bright resonator, strongly coupled with the incident THz wave. However, the SRR2 is not excited by the incident wave due to its symmetric structure with respect to the exciting electric field, thus acting as the dark resonator. By near-field coupling, an obvious PIT resonance is obtained via the destructive interference between the bright and dark mode in the unit cell composed of the SRR1 and the SRR2. For tuning the PIT resonance, a continuous monolayer graphene ribbon is placed under the split gap of SRR1.



**Figure 1.** (a) Schematic representation of the tunable plasma-induced transparency (PIT) metamaterial and the normal incident plane wave configuration. (b) Top view (from z axis) for the unit cell, the geometrical structure parameters are:  $Px = 100 \text{ } \mu\text{m}$ ,  $Py = 50 \text{ } \mu\text{m}$ ,  $l = 36 \text{ } \mu\text{m}$ ,  $w = 6 \text{ } \mu\text{m}$ ,  $g = 2 \text{ } \mu\text{m}$ .

In this work, the tunability of the proposed structure was studied numerically by using the finite-difference time-domain (FDTD) method. The unit cell was simulated under the periodic boundary conditions in the x-y plane. The perfectly matched layer boundary condition, maintaining computational convergence, was employed for the z direction. In the calculations, the mesh accuracy 4 is used to keep a balance between simulation time, memory requirements and accuracy. The simulation time is set to 800 picoseconds. In order to detect the transmission characteristics, a frequency-domain power monitor was placed under the substrate. The simulation is carried out on a small computing workstation, which has 64 Gigabytes memory and 16 central processing units. The permittivity of

Al,  $\varepsilon_{Al}(\omega)$ , characterizing the optical properties at the THz frequencies, can be determined using the Drude model [25],

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

where we assume that  $\omega_p = 2\pi \times 3.57 \times 10^{15} \text{ s}^{-1}$  and  $\gamma = 2\pi \times 1.98 \times 10^{13} \text{ s}^{-1}$ , for the plasma frequency and the damping constant, respectively. In terahertz range, the surface conductivity of graphene,  $\sigma_{gra}(\omega)$ , regarding as a function of angular frequency,  $\omega$ , can be described using the Drude-like model [26,27]:

$$\sigma_{gra}(\omega) = \frac{e^2 E_F}{\pi \hbar^2} \frac{i}{\omega + i/\tau},\tag{2}$$

where *e* is the basic unit charge,  $\hbar$  is the reduced Planck's constant,  $\tau = uE_F/(ev_F^2)$  is a parameter describing the carrier relaxation time, with  $E_F$  being the Fermi energy of graphene. In this paper, the Fermi velocity  $v_F = 1.1 \times 10^6$  m/s and the carrier mobility  $u = 3000 \text{ cm}^2/(\text{V} \cdot \text{s})$  are assumed, which are realistic for the monolayer graphene material [28]. Thus, as shown in Figure 2, the conductivity of graphene can be tuned as function of Fermi energy. According to the expression  $E_F \propto \sqrt{V_g}$  [29], the Fermi energy can be flexibly controlled by applying the external gate voltage  $V_g$ . Using the above strategy, an electric control of resonator response can be realized by varying the optical conductivity of the graphene layer.



**Figure 2.** The frequency dependent graphene surface conductivity with different Fermi energies: (a) real and (b) imaginary parts.

#### 3. Results and Discussions

The tunability of PIT resonance based on modifying the length parameter and relative distance of the SRRs have been widely studied by many groups [30,31]. Figure 3a presents the transmission spectra with different split gaps g. The different arrays, identified by the split gap g, present broad resonances range at THz regime. With the increase of split gap from 1 µm to 4 µm, the transparent peak moved from 0.47 THz blue to 0.54 THz, and the amplitude of transparency peak decreases form 0.86 to 0.80. In the inductive-capacitive (LC) resonance of SRRs, the split gap has a capacitance effect. The capacitance effect decreases with the increase of split gap. From the expression analysis,  $f \propto 1/\sqrt{LC}$ , the corresponding resonance frequency increases. The decrease of the transmission peak height indicates the reduction of the coupling between light and dark modes due to the smaller capacitance effect in the gap.



**Figure 3.** The tunable transmission spectra for the proposed PIT metamaterial: (**a**) with different gaps  $g = 1, 2, 3, 4 \mu m$ ; (**b**) numerical simulation and (**c**) analytical calculation for different Fermi energies.

Next, a continuous monolayer graphene ribbon, was integrated under the split gap of the bright resonator to obtain active control of PIT resonance, which was different than reported in literature [32,33]. The common dark mode control method basically controls PIT resonance by adjusting the transparency peak. However, the bright-mode tuning scheme mainly regulates the PIT resonance by shifting the resonance dips on both sides of the transparency peak. The transmission spectra, as the function of Fermi energy, are plotted in Figure 3b. It is worth noting that the PIT line shape can be clearly modulated with increase of Fermi energy. For example, the resonance dips at 0.46 THz and 0.56 THz, amplitude increase from 0.64 to 0.83 and from 0.76 to 0.8, respectively. The transparent window gradually broadens, but the frequency of the transmission peak is almost constant. When  $E_F = 0.8 \text{ eV}$ , the near-field coupling between the bright resonator. The complete modulation of the PIT resonance can be realized by merely shifting the Fermi energy of graphene, due to the sensitivity of SRRs to the conductive graphene layer.

The above modulation behaviors can be quantitatively described by the classical coupled two-particle model [34,35]:

$$\chi = \chi_r + i\chi_i \propto \frac{\omega - \omega_2 + i\frac{\gamma_2}{2}}{\left(\omega - \omega_1 + i\frac{\gamma_1}{2}\right)\left(\omega - \omega_2 + i\frac{\gamma_2}{2}\right) - \frac{\kappa^2}{4}}$$
(3)

Here, bright and dark resonators are plotted by subscripts 1 and 2, respectively.  $\omega_1(\omega_2)$  and  $\gamma_1(\gamma_2)$  are the resonance angular frequency and the damping rate, respectively. The parameter  $\kappa$  is introduced to represent the coupling coefficient between the two resonators, and  $\delta = \omega_2 - \omega_1$  represents the detuning of the resonance frequency of the dark mode from the bright mode. The imaginary part of susceptibility  $\chi_i$  determines the loss of energy in the system, thus, the transmission  $T(\omega)$  can be described through the formula  $T(\omega) = 1 - j\chi_i$ , where *j* is a geometric parameter describing the coupling strength of the bright mode resonator with the incident light.

The theoretical calculation results, shown in Figure 3c, are in good agreement with the simulated results except for slight deviations come from the effect related to the periodicity of the metamaterial [36]. Through the fitting parameters, as displayed in Figure 4a, one can see  $\gamma_2$ ,  $\delta$  and  $\kappa$  are roughly constant, whereas  $\gamma_1$  increases significantly with increasing  $E_F$ . Hence, the characteristic of modulation of the PIT resonance can be dominated by the variation of the damping rate in the bright resonator through the graphene layer. This implies that graphene layer with high conductivity in the gap tend to shorten the SRR1 circuit and reinforce the damping of the bright mode resonator. As the graphene Fermi energy increases, rising damping leads to reduce the LC resonance in SRR1 and suppresses the destructive interference between the bright mode resonator SRR1 and dark mode resonator SRR2. Finally, the damping rate  $\gamma_1$  becomes too large to sustain the bright mode excitation by the incident light, giving rise to the disappearance of the PIT effect. The coupled two-particle model and the coupled circuit model describe the same physical essence [17,37]. With the increase of the damping rate of the bright mode, graphene induced loss resistor, R<sub>Damp</sub>, describing the resistive loss of the graphene in the bright resonator, will increase gradually, which suppresses bright mode resonance. Despite the simplicity of the analytic model, the calculation results reflect the function of the graphene layer in the metamaterial structure and can be used to design hybrid metal-graphene devices.



**Figure 4.** (**a**) The fitting parameters for different Fermi energies. (**b**) The simulated spectra of the absorption in the PIT structure with different Fermi energies.

In order to further reveal the function of active two-dimensional graphene in the PIT device, the absorption,  $A(\omega)$ , is derived by the formula  $A(\omega) = 1 - R(\omega) - T(\omega)$  under different values for the graphene Fermi energies, where  $R(\omega)$  and  $T(\omega)$  denote the reflection and transmission, respectively. The absorbance spectra of PIT structure, as presented in Figure 4b, are normalized to that of the silicon

substrate. It can be clearly seen that the absorption of proposed PIT structure gradually increases with the increase of Fermi energy. In the terahertz band, the thickness of the monoatomic layer of graphene is much smaller than the skin depth of the terahertz wave, which can be regarded as a zero-thickness conductive film. Thus, varying the conductivity of graphene introduces tunable energy loss to the metamaterial modulating PIT resonance.

From the perspective of energy location, the electric field distribution at the resonance frequency can further reflect the modulation mechanism of PIT resonance, as shown in Figure 5. For the only metal-based PIT structure, the electric field is mainly focused around the gaps of bright mode SRR1 and dark mode SRR2, but the electric field strength SRR2 is stronger than that of SRR1, which is a typical PIT resonance distribution. However, for the structure with a graphene layer under the SRR1 gap, the electric field of the bright and dark resonators gaps are weakened. The former indicates that the coupling between the bright mode SRR1 and the incident electric field is reduced, and the latter means that the near-field coupling between dark mode SRR2 and the bright mode SRR1 is weakened. The introduction of the conductive graphene layer attenuates the capacitance effect of the SRR1 gap, resulting in the suppression of the bright mode resonance excited by the incident field. When  $E_F = 0.8 \text{ eV}$ , the electric field enhancement around the gap of dark resonator are completely suppressed since the destructive interference between the bright and dark modes disappears. Therefore, the modulation of PIT effect essentially results from the tunable conductivity of the graphene via changing the Fermi energy.



**Figure 5.** The distributions of electric field at the PIT resonance frequency for the cases of (**a**) without graphene; (**b**)  $E_F = 0.2 \text{ eV}$ ; (**c**)  $E_F = 0.8 \text{ eV}$ .

As well known, the strong phase dispersion within the transparency window can be used to slow down the speed of light. Generally, the slow light effect can be precisely depicted by the group delay [38],  $t_g = d\varphi/d\omega$ , where  $\varphi$  is the transmission phase shift. Figure 6 shows the group delay of the hybrid PIT metamaterial for the different Fermi energies. It can be observed, from no graphene to  $E_F = 0.8 \text{ eV}$ , the group delay of the transparency peak gradually decreases from 1.27 ps to 0.23 ps, corresponding PIT resonance decay process. Hence, the designed PIT device shows the ability of active modulation of slow light, which has potential applications in terahertz communication.



Figure 6. The group delay of the incident terahertz wave with different Fermi energies.

## 4. Conclusions

In general, the PIT tunable device, based on the interplay between monolayer graphene and coupled resonator arrays, has been demonstrated numerically in the lower terahertz regime. This compact configuration exhibits the perfect modulation of the transmission coefficient in the vicinity of a transparency peak, through adjusting the resonance of the bright mode resonator via shifting the Fermi energy of graphene. Based on the classical coupled two-particle model, the tunable PIT behavior can be attributed to the increasing damping rate of the bright mode in the metamaterial unit cell. Furthermore, the electric field distributions reveal that the physical mechanism of tunability lies in the tunable conductive effect of the graphene. In this work, monolayer graphene, operated as a tunable conductive film, can be applied directly to other coupled structures including split gap with capacitance effect, to further demonstrate its distinctive electromagnetic characteristics. This proposed scheme not only demonstrates the intriguing controllable light–matter interaction in the hybrid metal–graphene metamaterial, but also provides an active and ultrafast modulation appropriate for the demands of terahertz function devices.

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