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Broadband tunable terahertz plasmon-induced transparency in Dirac semimetals

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ABSTRACT

In this paper, we present a numerical and theoretical study on the realization of the tunable plasmon-induced transparency (PIT) effect at terahertz (THz) frequencies in Dirac semimetal (known as "three-dimensional graphene") metamaterials. The simulations reveal that the PIT effect is generated because of the excitation of the dark mode that can be regarded as a dipole. Further investigation reveals that the bandwidth can be broadened while the resonant frequencies of the PIT remain unchanged. At the same time, the resonant frequency of the PIT window can be dynamically tuned by changing the Fermi energy of the Dirac semimetals instead of refabricating the structures. Moreover, a figure of merit value of about 10.55 is achieved in our proposed design based on the performed sensitivity measurement. Our study can provide guidance for various THz devices in practical applications.

1. Introduction

Electromagnetically induced transparency (EIT) is a quantum interference effect in laser-activated atomic systems and induces a narrow transparency window within a broad absorption spectrum [1]. This novel effect has a wide range of potential applications because of its sharp dispersion and violent resonance, however, the performance of the EIT is strictly constrained by harsh conditions such as cryogenic temperatures, coherent pumping, and stable gas lasers, among others [2,3]. Recently, plasmon-induced transparency (PIT), an EIT-like optical effect in metamaterials, has attracted much attention because of its significant advantages and broad range of practical applications, such as biological and chemical sensing [4–6], active plasmonic switches [7,8], optical storage [9,10], and polarization conversion [11]. Two efficient ways that the bright–dark coupling [5,7,12–15] and bright–bright coupling [16–20] are widely used to induce EIT-like effect in plasmonic metamaterials. The former is based on the destructive interference between the bright and dark mode, while the latter is based on the weak hybridization between two bright modes. Zhang et al. [13] first demonstrated an EIT-like effect by using a dolmen-like structure based on bright-dark mode near-field coupling. Zhu et al. [21] proposed a simple structure of two parallel coupling coplanar metallic strips to obtain the PIT effect based on bright–bright coupling. Han et al. [22] proposed a back-to-back self-asymmetric split-ring resonator (SRR) to construct an EIT-like system, where the left gap is regarded as bright mode and the right one is regarded as dark mode. Wang et al. [23] designed a novel planar metamaterial consisting of a nanoring and a nanostrip to achieve a plasmonic EIT-like effect and both two elements serve as bright modes. Because of the difficulty of modulation of the PIT window, graphene gradually replaces the traditional metallic metamaterials and provides a promising platform to design tunable PIT systems [24,25].

Three-dimensional (3D) Dirac semimetals known as 3D graphene [26] have attracted great attention in physics and material science recently, due to its dramatic properties such as extremely high mobility [27], ultrafast transient time [28], and low energy photon detection [29]. Compared to monoatomic layer graphene, 3D Dirac semimetals are more robust against environmental defects or excess conductive bulk states. Most importantly, the surface conductivity of Dirac semimetals can also be dynamically controlled by changing the Fermi energy, which is significant to design tunable devices. In our previous work [30], a tunable PIT system using two parallel Dirac semimetal films (DSFs) serving as bright modes has been demonstrated, where the weak hybridization between two bright modes with frequency detuning gives rise to the PIT effect at THz region.

In this paper, bright-dark mode coupling method is used to realize tunable PIT effect at the THz frequencies, where two side strips serve as bright modes and the central strip serves as a dark mode. By analyzing the z-component of the electric field distribution at

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the resonant frequencies, we find that the PIT phenomenon is produced by the electric field transferred from the bright modes to the dark mode. At the same time, the transparency bandwidth can be broadened by simply adjusting the lateral displacement between two bright modes. The resonant frequency of the PIT can be actively modulated by changing the Fermi energy of the DSFs, and an ultrahigh transmission intensity of nearly 99.9% is achieved in our work. Finally, by measuring the sensitivity a figure of merit (FOM) of about 10.55 is obtained in our design. The results indicate that this PIT system based on 3D Dirac semimetals could have potential applications in tunable sensors, switches, filters, slow-light devices, and other THz devices.

2. Simulation and model

A basic unit of the designed DSF plasmonic structure on a substrate for realizing PIT is depicted in Fig. 1 and is a combination of radiative and dark elements. The radiative elements that are regarded as bright modes consist of two parallel identical Dirac semimetal strips with length L = 26 μm and width w = 6 μm lying along the x-direction, while the central strip with the same length and width as the side strips serves as the dark mode. The unit cell of the design can be described by horizontal and vertical periodicities of $P_x = 115\mu m$ and $P_y = 65\mu m$, respectively. The thickness of the Dirac semimetal strips is set as 0.2μm and the refractive index (RI) of the substrate is considered to be 1.5 [31]. The incident waves irradiate along the z-direction with an E_x polarization. The FDTD method are employed to numerically study the properties of the 3D Dirac semimetal based PIT system. We set a perfect electric boundary and perfect magnetic boundary in the x and y directions, respectively. An open boundary condition is set along the z direction.

The dynamic conductivity of the Dirac semimetal can be derived using the random-phase approximation at the long-wavelength limit, including both the intraband and interband processes [26]:

$$\mathrm{Re}\sigma(\Omega) = \frac{e^2}{h}\frac{gk_F}{24\pi}\Omega G(\Omega/2) \tag{1}$$

$$\mathrm{Im}\sigma(\Omega) = \frac{e^2}{h}\frac{gk_F}{24\pi^2}\left[\frac{4}{\Omega}\left(1+\frac{\pi^2}{3}\left(\frac{T}{E_F}\right)^2\right) + 8\Omega\int_0^{\varepsilon_c}\left(\frac{G(\varepsilon)-G(\Omega-2)}{\Omega^2-4\varepsilon^2}\right)\varepsilon d\varepsilon\right] \tag{2}$$

where $G(E) = n(-E) - n(E)$ with $n(E)$ being the Fermi distribution function, E_F is the Fermi level, $k_F = E_F/\hbar v_F$ is the Fermi momentum, $v_F = 10^6 m/s^{-1}$ is the Fermi velocity, $\varepsilon = E/E_F$, $\Omega = \hbar\omega/E_F$, $\varepsilon_c = E_c/E_F$ ($E_c = 3$ is the cutoff energy), and g is the degeneracy factor. Fig. 2 gives the surface conductivity of 3D Dirac semimetal and graphene, and the labels 1 and 2 represent 3D Dirac semimetal and graphene, respectively.

Using the two-band model and taking into account the interband electronic transitions, the permittivity of the 3D Dirac semimetals can be written as:

$$\varepsilon = \varepsilon_b + i\sigma/\omega\varepsilon_0 \tag{3}$$

where ε_b is the effective background dielectric and $\varepsilon_b = 1$ for g = 40 (AlCuFe quasicrystals [32]) and ε_0 is the permittivity of vacuum.

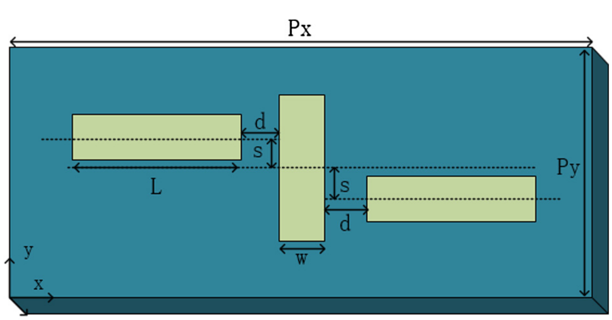

Fig. 1. Schematic of the Dirac semimetal structures. The coupling distance between the side strips and central strip is d, the lateral displacement is s, and the width w and length L of these strips are 6 and 36 μm, respectively.

3. Results and discussion

To reveal the mechanism of the PIT effect, we numerically investigate the transmission spectrum of the design with different lateral displacements s under identical Fermi energies ($E_F = 70$ meV) and coupling distances (d = 2.5 μm), as shown in Fig. 3a–d. From Fig. 3a. We can clearly see that only one resonance dip is obtained at 1.605 THz when s = 0 μm because of the surface plasmon resonance excitation of the two side DSF strips. As the side strips have the same length along the polarization of the electric field, they exhibit the same resonance mode (~1.605 THz). Moreover, the length of the central strip along the polarization direction is so short that the resonant frequency falls on the outside of the measurement range [33]. By increasing the lateral displacement s to 0.5 μm, a miniscule transmission peak appears at 1.611 THz, as shown in Fig. 3b. Further increasing the lateral displacement s, an apparent transmission peak appears at 1.611 THz and its strength is associated with the increase in s. Finally, an extremely high transmission intensity reaching 99.7% is obtained when s = 2.5 μm.

The three-level model [13] can be employed to theoretically explain the transmission mechanism. As demonstrated above, in our simulation, the side DSF strips serving as bright modes (state ⟨0|) can be directly and strongly interact with the incident light (ground state ⟨1|). As the central DSF strip is excited by the bright modes and cannot directly interact with the incident light, the central DSF strip serves as dark mode (state ⟨2|). The dipole modes coupling in this simulation can be describes with two possible ways: ⟨0| – ⟨1| and ⟨0| – ⟨1| – ⟨2| – ⟨1| interfering with each other destructively, which leads to the emerging of the transparency window in the spectrum. Both pathways can be described as the linearly Lorentzian oscillator model:

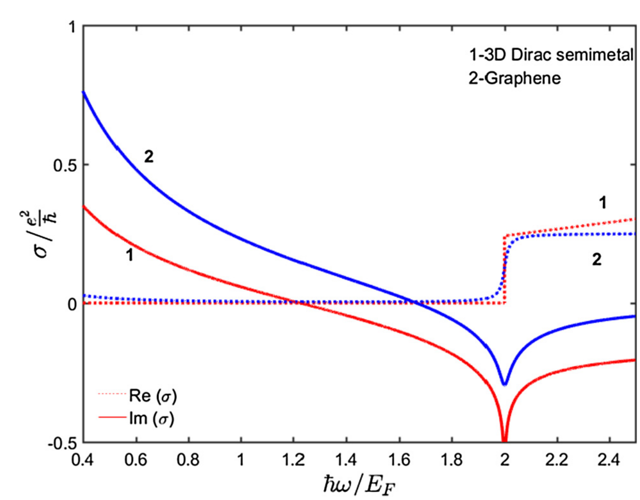

Fig. 2. Real and imaginary parts of the surface conductivity for 3D Dirac semimetal and graphene in units of $e^2/\hbar$ as a function of the normalized frequency $\hbar\omega/E_F$. The parameters are set as $g = 40$ and $\mu = 3\times10^4 cm^2V^{-1}s^{-1}$(the intrinsic time $\tau = 4.5\times10^{-13}$s).