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Tunable multiple plasmon-induced transparency in three-dimensional Dirac semimetal metamaterials

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ABSTRACT

Tunable plasmonic Dirac semimetal metamaterials featuring multiple transparency windows in the terahertz (THz) frequency region are numerically investigated in this study. The proposed multiple plasmon-induced transparency (PIT) system is composed of two types of H-shaped structures, each of which can be regarded as an independent PIT system. Unlike in the conventional metallic PIT systems, the multiple PIT effect in three-dimensional Dirac semimetals can be tuned by varying the Fermi energy instead of the geometrical parameters. The proposed multiple PIT structure could pave the way for potential applications in various areas such as multiple-frequency slow-light devices, optical sensing, and active plasmonic switching.

1. Introduction

Electromagnetically induced transparency (EIT) is a quantum interference effect in laser-activated atomic systems, which can significantly change the optical properties of a medium [1]. This novel effect is promising for applications in optical storage and slow light owing to its sharp dispersion and violent resonance. However, the EIT performance is significantly hindered by the demanding conditions to preserve the quantum state coherence [2]. The merging of plasmonics and metamaterial areas paves the way for new perspectives for an ultimate control of light at the deep sub-wavelength scale. Plasmon-induced transparency (PIT) based on metamaterials [3–7] is an EIT-like optical effect, which has attracted a significant attention owing to its advantages and broad range of practical applications, such as biological and sensitive sensors [8–10], active plasmonic switches [11,12], and optical storage [13,14]. Various plasmonic metamaterial structures, including cut wires [3,15,16], split-ring resonators [4,17,18], and coupled waveguide resonators [19], have been proposed and widely used to achieve the PIT effect. However, changes of the geometric parameters of structures were needed to modulate the PIT spectrum in most metal-based metamaterial structures.

Graphene, a typical two-dimensional (2D) Dirac semimetal, has been widely used for tunable plasmonic devices and systems [20–24], benefiting from its desirable optical properties including strong light confinement [25], low plasmonic losses [26,27], and very advantageous property of electrical tunability [28]. Three-dimensional (3D) Dirac semimetals, a novel state of quantum matter, have recently attracted a considerable attention in physics and materials science. As a 3D analogue of graphene, 3D Dirac semimetals possess all of the advantages of graphene as a photosensitive material, and potentially exhibit a stronger interaction with light as a bulk material and thus enhanced responsivity. Compared to graphene and surface states of a topological insulator [29], 3D Dirac semimetals are more robust against environmental defects or excess conductive bulk states [30]. Moreover, owing to the crystalline symmetry protection against gap formation [31–33] in a 3D Dirac semimetal, the mobility (9×10^6 cm^2 V^{-1} s^{-1} at 5 K) is very high [34], significantly higher than that of the best graphene sample (2×10^5 cm^2 V^{-1} s^{-1} at 5 K) [35]. Consequently, the stable 3D Dirac semimetal is a promising material platform for various plasmonic devices. In our previous study [36], a simple tunable PIT system using 3D Dirac semimetal films (DSFs) was proposed; the weak hybridization between two bright modes leads to the original PIT effect. However, most of the above studies focused on the single PIT effect; a system with multiple transparency windows, in particular, a tunable multiple PIT system, is highly desirable for various applications.

In this study, instead of a conventional metal or graphene, a new 3D Dirac semimetal material is numerically investigated to realize a tunable multiple PIT effect in the THz region. The multiple PIT system consists of two types of H-shaped structures, each of which consists of a central and two side DSF strips acting as the bright and dark modes, respectively. Single and multiple transparency windows are obtained. Furthermore, the multiple PIT spectrum can be tuned by varying the Fermi energy

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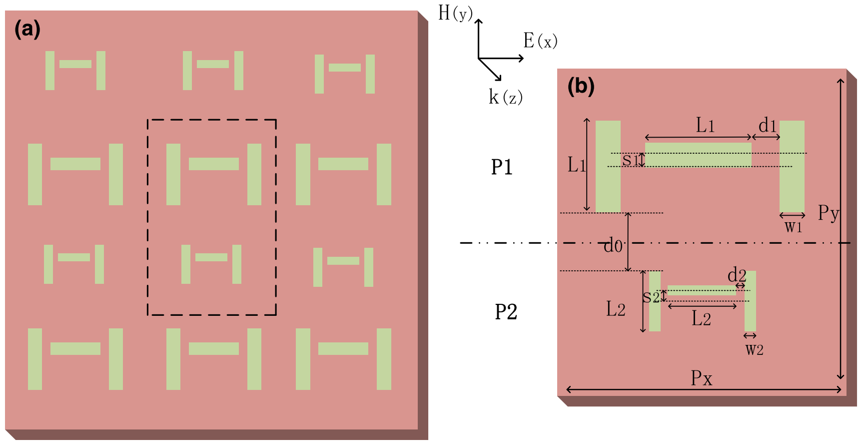

Fig. 1. (a) Schematic of the multiple PIT system. The black dashed box outlines a unit cell containing two PIT structures with different sizes. (b) Unit cell consisting of the upper and lower PIT structures denoted as P1 and P2, respectively. The parameters s_1 in P1 and s_2 in P2 are variables.

of the 3D Dirac semimetals instead of reoptimizing the geometrical parameters, which could be useful in tunable sensors, modulators, multiple-frequency slow-light devices, and other THz devices.

2. Models and simulations

The schematic of the multiple PIT system composed of the H-shaped DSFs fabricated on a substrate with a refractive index considered to be 1.5 [37] is illustrated in Fig. 1(a). A basic unit of the designed 3D Dirac semimetal plasmonic structure is depicted in Fig. 1(b), which is a combination of two types of H-shaped structures with different sizes. For convenience, we define the large and small H-shaped structures as P1 and P2, respectively; each of them can be regarded as a PIT system. In P1, both central and two side strips have lengths of $L_1 = 36$ μm and widths of $w_1 = 6$ μm; the separation between the central strip and side strips is fixed to $d_1 = 3$ μm; the lateral displacement is denoted as parameter s_1. In P2, both central and two side strips have lengths of $L_2 = 22$ μm and widths of $w_2 = 3$ μm; the separation between the central strip and side strips is also fixed to $d_2 = 3$ μm; the lateral displacement is denoted as parameter s_2. The separation between the P1 and P2 systems is fixed to $d_0 = 36$ μm. The unit cell of the design can be described by horizontal and vertical periodicities of $P_x = 105$ μm and $P_y = 130$ μm, respectively. The thickness of the Dirac semimetal strips is set to 0.2 μm. The incident waves irradiate perpendicularly to the x–y plane with an E_x polarization. All of the 3D Dirac semimetal plasmonic strips are numerically investigated using the CST Microwave Studio. Perfect electric and magnetic boundaries are employed in the x- and y-directions, respectively. An open boundary condition is employed along the z-direction.

The dynamic conductivity of the Dirac semimetal can be derived using the random-phase approximation (RPA), including both intraband and interband processes [38]:

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

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

where $G(E) = n(-E) - n(E)$, $n(E)$ is the Fermi distribution function, E_F is the Fermi energy, $k_F = E_F/\hbar v_F$ 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. Using the two-band model and considering the interband electronic transitions, the permittivity of the 3D Dirac semimetal can be expressed as:

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

where ε_b is the effective background dielectric constant ($\varepsilon_b = 1$ for $g = 40$ (AlCuFe quasicrystals [39])) and σ_0 is the permittivity of vacuum. In our calculation, the electron mobility is $\mu = 3\times10^4$ cm^2 V^{-1} s^{-1} (the relaxation time is $\tau = 4.5\times10^{-13}$ s). The 3D Dirac semimetal can be characterized by permittivity values under different frequencies in the simulation processes.

3. Results and discussion

We numerically study the bright and dark modes in the P1, P2, and P1–P2 structures. The transmissions of the P1–P2 system, structure with only the central strip (bright mode), and structure with only the two side strips (dark modes) are simulated using the finite-difference time-domain (FDTD) method, as shown in Fig. 2. The Fermi energy of 70 meV was unchanged in all of the simulations in this case. In the simulations of Fig. 2(a), there is no P2 structure on the substrate, and a typical localized surface plasmon (LSP) resonance of the structure with only the central strip is excited by an incident wave with an E_x polarization, as indicated by the green dashed line. An LSP resonance of the structure with only the side strips is excited by an E_y instead of E_x polarized incident wave, as indicated by the blue dashed line. The PIT effect with a resonant frequency of approximately 1.656 THz emerges in the transmission spectrum when the P1 system is excited by the incident wave with an E_x polarization, shown by the red solid curve in Fig. 2(a). In the simulations of Fig. 2(b), there is no P1 structure on the substrate; the simulated results of the P2 structure are generally similar with those of the P1 structure.

The Lorentzian oscillator model is employed to explain the transmission mechanism of the multiple PIT system in our design. The bright and dark modes in the P1 and P2 structures are expressed as $|D_{1,2}\rangle$ and $|Q_{1,2}\rangle$, respectively. The subscripts 1 and 2 correspond to the P1 and P2 structures, respectively. The multiple PIT structures can be described as a three-level system [3] with two pathways of $|0\rangle - |D_{1,2}\rangle$ and $|0\rangle - |D_{1,2}\rangle - |Q_{1,2}\rangle - |D_{1,2}\rangle$ (ground state $|0\rangle$, $|0\rangle - |D_{1,2}\rangle$ as a dipole-allowed transition, and $|0\rangle - |Q_{1,2}\rangle$ as a dipole-forbidden transition [40]) interfering with each other destructively, resulting in the transparency peak in the resonance notch. The field amplitudes of $|D_{1,2}\rangle$ and $|Q_{1,2}\rangle$ are obtained by [41]:

$$\begin{bmatrix} \omega-\omega_{D,1}+i\gamma_{D,1} & \kappa_1 & 0 & 0 \\ \kappa_1 & \omega-\omega_{Q,1}+i\gamma_{Q,1} & 0 & 0 \\ 0 & 0 & \omega-\omega_{D,2}+i\gamma_{D,2} & \kappa_2 \\ 0 & 0 & \kappa_2 & \omega-\omega_{Q,2}+i\gamma_{Q,2} \end{bmatrix} \times \begin{bmatrix} \tilde{D}_1 \\ \tilde{Q}_1 \\ \tilde{D}_2 \\ \tilde{Q}_2 \end{bmatrix} = -\begin{bmatrix} g_1\tilde{E}_0 \\ 0 \\ g_2\tilde{E}_0 \\ 0 \end{bmatrix} \tag{4}$$