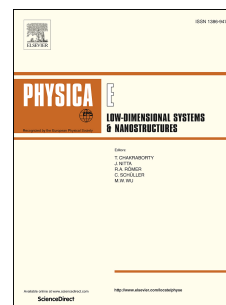


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Dynamically tunable electromagnetically induced transparency in a terahertz hybrid metamaterial

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Abstract

A novel mechanism to realize dynamically tunable metamaterial analogue of electromagnetically induced transparency (EIT) in the terahertz (THz) regime is proposed. By putting a monolayer graphene under the dark resonator, the amplitude of the EIT resonance in the metal-based metamaterial can be substantially modulated via altering the Fermi level of graphene. The amplitude modulation can be attributed to the change in the damping rate of the dark mode caused by the recombination effect of the conductive graphene. This work provides an alternative way to achieve tunable slow light effect and has potential applications in THz wireless communications.

Keywords:

terahertz, metamaterial, graphene, electromagnetically induced transparency, slow light

1. Introduction

The electromagnetically induced transparency (EIT) effect is of great interest in many important applications, such as slow light, optical switching and nonlinear devices. This effect was first demonstrated in three-level atomic systems, where the destructive interference between two radiative transitions creates a sharp transparency window within a broad absorption spectrum.[1] However, quantum EIT requires complicated experimental handlings, such as stable gas lasers and low temperature environment, which constraint its practical implementation in chip-scale applications. Recently, metamaterial analogues of EIT based on the near field coupling between the bright and dark resonators have been intensively investigated because of the flexible design and easy implementation[2, 3, 4, 5]. These EIT metamaterials bring the original quantum effect into the realm of classical optics and show great potentials in developing novel plasmonic devices.

In practice, the ability to dynamically tune EIT effect has attracted enormous attention. For most EIT analogues based on metallic materials with a fixed spectral response, it is difficult to manipulate the EIT response without changing the geometries or modifying the supporting substrates. For this, the EIT metamaterials are integrated with active materials, such as semiconductors,[6, 7], superconductors,[8] and nonlinear materials.[9, 10] Alternatively, graphene can be an excellent candidate for designing tunable devices in the terahertz (THz) regime. Its surface conductivity can be tuned by shifting the Fermi level, which may be potentially varied from -1 to 1 eV

by chemical doping or electrostatic gating.[11, 12] Moreover, the graphene-based metamaterial devices show high modulation speed, compared with other counterparts.[13, 14] Hence recent studies have proposed a variety of graphene-based metamaterials to generate controllable EIT analogues.[15, 16, 17, 18, 19, 20, 21, 22, 23] However, the surface conductivity of the discrete graphene resonator is difficult to be tuned, restricting the practical applications.

In this work, we propose a THz hybrid EIT metamaterial by integrating a controllable monolayer graphene into the metal-based metamaterial composed of a cut wire (CW) and a pair of split-ring resonators (SRRs). A significant amplitude modulation of the EIT resonance is demonstrated by shifting the Fermi level of graphene. Based on the investigation of the coupled harmonic oscillator model and electrical field distributions, the modulation can be attributed to the change in the damping rate of the dark mode caused by the recombination effect of the conductive graphene. The proposed EIT metamaterial achieves the dynamically tunable group delay and shows promising applications in developing compact slow light devices.

2. The geometric structure and numerical model

The schematic geometry of our proposed EIT metamaterial is depicted in Figure 1(a). The unit cell is composed of a pair of SRRs symmetrically placed on the left and right sides of a CW, and a monolayer graphene is deposited on the bottom of the SRR-pair. The specific geometrical parameters are described in Figure 1(b). The SRR-pair and CW are both made of 200 nm-thick aluminum (Al). The THz characteristics of Al are modeled by the complex permittivity $\varepsilon_{Al} = \varepsilon_{\infty} - \omega_p^2/(\omega^2 + i\omega\gamma)$,

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