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Theoretical realization of dynamically tunable double plasmonically induced transparency in a graphene-based waveguide structure

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ABSTRACT

A graphene-based waveguide coupled with radiative and subradiant graphene ribbon resonators is proposed to represent the four-level energy diagram in conventional atomic systems and demonstrate a new realization of dynamically tunable double plasmonically induced transparency (DPIT). The radiative resonator is achieved with the help of direct coupling from the graphene waveguide while indirect coupling is relied for the subradiant resonator. By combining the numerical simulation results and the dressed theory, the physical mechanism behind the DPIT is presented in detail. The DPIT phenomenon is derived from the mode splitting caused by the phase-coupled effects. By controlling the Fermi energy level of graphene ribbon, the double transparency windows can be dynamically tuned. The proposed structure may find its application in optical communication or other novel terahertz integrated optical circuits and devices.

1. Introduction

Surface plasmon polaritons (SPPs), are evanescent electromagnetic waves that propagate along a metal-dielectric interface as a result of collective electron oscillations coupled to an external electromagnetic field [1]. A considerable amount of research has been carried out on SPPs owing to their capability in enhancing the local optical fields and breaking the diffraction limit, which stimulate the development of highly-integrated optical devices at nanoscale [2]. To date, numerous fascinating phenomena based on SPPs have been proposed and investigated experimentally or theoretically, such as Bragg reflectors [3,4], sensors [5,6], optical switching [7] and so on.

Graphene, a monolayer of carbon atoms arranged in a honeycomb lattice, has exhibited many unique and fantastic properties in electronics since its successful fabrication [8–10]. Beyond pure electronic properties, graphene attracts significant research interest for the excitation of plasmons in atomic scale [11–13]. Graphene plasmonics is regarded as a promising technology for strong light-matter interactions in terahertz (THz) and infrared frequencies region due to the special behaviors similar to metals [14]. Most importantly, SPPs generated in graphene exhibit the favorable characteristics that make graphene a remarkable alternative to metal-based plasmonics such as extreme electromagnetic confinement, relatively low dissipative loss and dynamic tunability by changing the doping level via the electrostatic or chemical gating [15,16]. These unique features make graphene an excellent candidate for highly tunable plasmonic and optoelectronic devices.

It is well-known that a Λ-type three-level atomic medium can become transparent to a weak probe field by applying a strong coupling field, which is the result of the destructive interference between two different excitation pathways to the upper level. This phenomenon is called electromagnetically induced transparency (EIT) [17]. A great many interesting applications based on EIT have appeared in a wide range of fields, such as slow light, enhanced optical nonlinearities and optical information storage [18,19]. Recently, double electromagnetically induced transparency (DEIT), as an extension of EIT, has been proposed and demonstrated as a vehicle for extending the utility of EIT by creating transparency conditions for two signal fields simultaneously [20]. This provides the possibility for coherent control [21] and enabling long-lived

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nonlinear interactions between weak fields [20]. DEIT allows propagation of the two signal fields with minimal loss and increases the interaction time between pulses owing to group-velocity reduction. These capabilities make DEIT a promising candidate for numerous applications in quantum computation and communication [22]. The research on the DEIT has aroused much interest of scientists recently [22–24]. However, the realization of DEIT in atom systems needs extreme experimental conditions like cryogenic conditions and gaseous medium, which restrict its practical applications [18]. Fortunately, in recent years, mimicking EIT in classical configurations has been proposed and demonstrated to display the EIT-like spectral responses by scientists [25,26]. Among these EIT-like phenomena, one class of EIT-like phenomena which is based on plasmonic resonances is known as plasmonically induced transparency (PIT). The PIT has been extensively studied due to its excellent, feasible, and wide practical applications [27–29]. Thus, it will be interesting to achieve the double plasmonically induced transparency (DPIT) in classical plasmonic configuration systems to extend the application of EIT.

Motivated by the above fundamental studies, in this paper, we use mutually coupled radiative and subradiant graphene ribbon resonators and a graphene waveguide representing the four-level energy diagram atomic system to realize a dynamically tunable DPIT. The graphene-based waveguide structure is consisted of a graphene waveguide and three side-coupled graphene ribbons. We analyze the physical mechanism of DPIT in our structure in detail with the dressed theory and numerical simulations. It is found that the DPIT phenomenon is derived from the mode splitting caused by the phase-coupled effects. In addition, we show the transparency windows of DPIT can be dynamically tuned by changing the Fermi energy level of graphene ribbon rather than through reconstructing the configuration.

2. Physical structure

A quasi Λ-type four-level configuration system is adopted for the demonstration of the DPIT. The energy level scheme of the four-level system is given in Fig. 1(a). $|1\rangle$, $|2\rangle$ and $|3\rangle$ are the ground state hyperfine levels, and $|4\rangle$ is excited state. The states $|1\rangle$ and $|3\rangle$ can direct couple to the state $|4\rangle$ and the state $|2\rangle$ and $|3\rangle$ can couple with each other. While the transition between $|1\rangle$ and $|2\rangle$ is forbidden. The corresponding graphene based structure is illustrated in Fig. 1(b), which is formed by graphene nanostructures embedded in a dielectric material with a relative permittivity of $\varepsilon = 2.25$. Graphene is treated as an ultra-thin anisotropic material with a thickness of $\Delta = 1$ nm. The in-plane permittivity of graphene is [30] $\varepsilon_{\parallel} = 1 + i\delta/\Delta\omega\varepsilon_0$, while the out-of-plane permittivity is a constant $\varepsilon_{\perp} = 2.5$, where δ and ω stand for graphene's surface conductivity and the light angular frequency. The surface conductivity of graphene is written as [14] $\delta = ie^2E_F/\pi\hbar^2(\omega + i\tau^{-1})$. e, E_F, $\hbar$ are the electron charge, Fermi energy level and reduced Planck constant, respectively. $\tau = \mu E_F/ev_F^2$ is the intrinsic relaxation time, where $v_F = c/300$ is Fermi velocity and $\mu = 100000\ \mathrm{cm}^2/\mathrm{Vs}$ is the DC mobility. In Fig. 1(b), three graphene ribbons are arranged upon the graphene waveguide and the width of the three ribbons (W) is in constantly kept as 250 nm. d_1, d_2 and d_3 are the distance between the graphene ribbons and graphene waveguide. In this paper, we only consider the transverse magnetic (TM) polarized SPP modes propagate our structure. The eigen SPP modes are injected from the left side of the graphene waveguide. The finite element method is used for the numerical simulations and by scanning the frequency of the incident light, the transmission spectrum can be obtained.

3. Results and discussion

Nowadays, the graphene nanoribbon can be treated as a novel resonator, where the plasmonic resonant mode can be excited by means of strong optical coupling to the waveguide and dynamically controlled by gate voltage [30]. We know that one of important factors to determine the excitation is the coupling distance between the graphene ribbon and the bottom graphene waveguide. Therefore, it is necessary for us to study the distance-dependence of graphene ribbon and determine an appropriate distance between the graphene ribbon and the bottom graphene waveguide. To show the distance-dependence property, we study a simple structure in which there is only one single graphene ribbon placed on the side of graphene waveguide. The Fermi energy levels of the graphene waveguide and the graphene ribbon are set to be $E_{fg} = 140$ meV and $E_{fr} = 160$ meV or 180 meV, respectively. Fig. 2(a) shows the transmission spectra of the system for graphene ribbons with different distances from the graphene waveguide and different Fermi energy levels. For $E_{fr} = 160$ meV, we can find that a deep transmission dip at 10.65 THz appears at the distance $d = 200$ nm, as shown in Fig. 2(a). It is attributed to the strongly near-field coupling between the graphene waveguide and the localized the graphene ribbon. As the coupling distance increases, the resonance frequency of the depth of the transmission dip decreases due to the weakening of the coupling between the graphene waveguide and ribbon resonator. When the distance is increased to 500 nm, the transmission dip disappears, which means that the graphene ribbon cannot be excited. In addition, for $E_{fr} = 180$ meV, we also find that the transmission also disappears when the distance is increased to 500 nm.

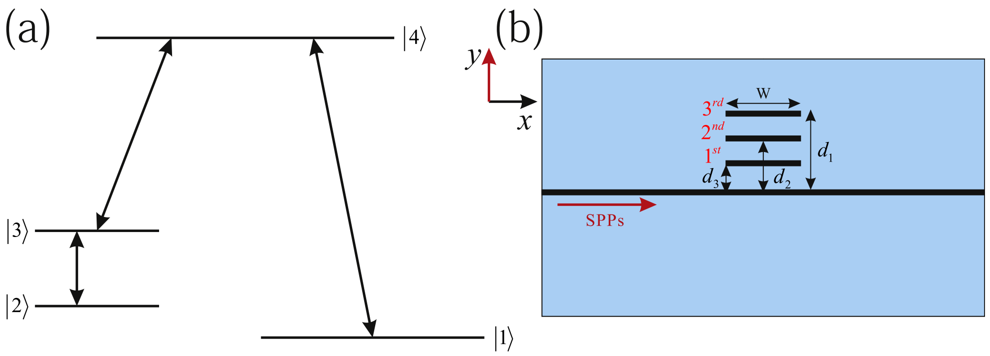

Fig. 1. (a) Energy level diagram of a quasi Λ-type four-level atomic system; (b) three graphene ribbon resonators coupling to the graphene waveguide represents the four-level diagram in Fig. 1(a). The graphene waveguide and ribbons are stacked along vertical direction: y axis.