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Surface plasmon-induced transparency in a cut wire-coupled graphene split ring resonator

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ABSTRACT

In this paper, a cut wire (CW)-coupled, orthogonally distributed graphene split ring (GSR) resonator is proposed to realize the optical analogy of electromagnetically induced transparency (EIT) in the mid-infrared regime. The dipolar surface-induced bright mode resonance of the GSR interferes constructively or destructively with the dark modes, which develops a rather pronounced transparency window in the absorption profile. This transparency is mainly attributed to the superposition of the interference effect, thus providing an alternative way of mimicking EIT in the classical optical field. The polarization of the incident beam and the position where the CW is located play significant roles in resonance modulation. The resonant wavelength and the bandwidth of the transparency window can be tuned by changing the geometrical parameters or the optical properties of graphene. The proposed device is sensitive to the substrate index and the corresponding resonant wavelength shift can be applied to detect this change; furthermore, ultra slow light with group index of over 992 is realised within the transparency window. These results may find potential use in optical sensors and switches.

1. Introduction

Electromagnetically induced transparency (EIT) was first observed and studied in multilevel (typically three-level) atomic systems because of the considerable modification in the optical properties of the medium [1]; it is induced by a weak probe field and a strong coupling light field. Earlier reports demonstrated that the principle could be attributed to the destructive interference between the probe field-driven excitation pathway and the coupling field-driven excitation pathway [2]. Because of the destructive interference from the metastable state to the upper state driven by the coupling light field, the previously populated upper state becomes unpopulated, whereas the ground state becomes populated. Thus, an opaque system becomes transparent at the coupling resonant frequency. This attractive phenomenon has various potential applications such as lasing without inversion [3], coherent population trapping [4], Autler-Townes splitting [5], slowing light [6], enhancing nonlinear effect [7], signal processing [8], and optical switching [9]. However, the difficulty to find proper nonlinear materials [10] and the extreme experimental conditions [11] significantly restrict the applications of quantum EIT effect.

Fortunately, the classical optical analogy of EIT in the infrared or terahertz (THz) region realized in metastructures or metamaterials [12] has opened up a new way for investigating the appealing EIT phenomenon. Usually, the artificially built metastructures consist of a bright mode [13,14], which is directly illuminated by the incident field, and an adjacent dark mode [15],which is not directly excited by the probe field, but the excitation can be induced by the bright mode. When the light coupled into the dark mode returns to the bright mode, the phase information is altered. Thus, the direct transition pathway from incident field destructively interferes with the field coupled back from the dark mode which cancels the bright resonance while conversely, the dark mode is fully excited. Such schemes are reported in our previous works [16,17]. Another way of mimicking EIT is by breaking the structure symmetry [18–20]. All the above ways are based on the principle of surface plasmon (SP) resonance at dielectric interfaces [21]. The SPs have a tight field confinement [22] and low dissipation loss [23]; most importantly, they can overcome the diffraction limit, which enables them to work on sub- or deep subwavelength scale [14,24,25]. Such devices are usually highly integrated and ultra-compact in size. Furthermore, an excellent tunability can be achieved in graphene-based metamaterials [26–29] by either passive chemical doping [30] or external gate biasing [31] over a wide range of Fermi energy level. Experimental verifications have shown some existing examples; to name one, in [32], it was successfully demonstrated that in

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graphene, which is a two-dimensional sheet of carbon atoms, plasmon polaritons and their associated optical fields can readily be tuned electrically by varying the graphene carrier density; these optical fields are observed by the near-field scattering microscopy with infrared excitation light. In other research fields such as graphene plasmon-enhanced absorption [33,34], the modification of the geometric dimensions plays an important role in the spectral response modulation as well, thus providing another way to investigate the tunability of graphene-based metastructures.

In this paper, we propose a different scheme for mimicking the EIT effect in two graphene-based split ring (GSR) resonators, which are mutually coupled by a graphene cut wire (CW). When the CW between the two GSRs is moved to the asymmetric positions in the vertical direction, the spectral responses show an EIT-like transmission. The polarization direction of the incident beam affects the performance of the hybrid resonator; therefore, it is numerically investigated. Furthermore, we perform research on the sensing ability of the device and calculate its sensitivity with respect to the substrate refractive index. By considering the geometrical parameters of the device and the optical properties of graphene, their influence on the resonant wavelength and the bandwidth of the transparency window is determined. Then, the light within the transparency window yields a high group index, which means that the light travels slowly when it passes through the graphene tunnel. Conclusions are drawn in the last section.

2. Simulation setup for mimicking the EIT effect

The hybrid SP resonator comprises a pair of orthogonally distributed identical square-shaped split graphene rings, which are mutually coupled by a graphene CW horizontally, as illustrated in Fig.1. The layout shows a unit cell whose periodicity is P_x nm in x direction and P_y nm in y direction. The length of the square-shaped GSR is L nm, the gap distance of the SR is g nm, and the length of the CW is l nm. In this paper, the graphene strip width w nm of all resonators is constant. The finite difference time domain (FDTD) method is used to calculate the spectral response, the phase shift, and the field amplitude distributions in the commercial Lumerical FDTD software. The settings are as follows. The boundaries are periodic in x and y directions, while the perfectly matched layers are used in the z direction to eliminate the reflected waves. The graphene permittivity data are calculated by fitting the 3D volumetric model provided in the FDTD material database; in this model, the Fermi energy is 0.64 eV, the carrier mobility is $1m^2/V/s$ [35,36], and the thickness is 0.335 nm [37]. For a simple demonstration of the EIT phenomenon, we keep the triple hybrid resonator isolated in air.

Before we combine the GSRs and the CW to demonstrate the EIT-like phenomenon, we first investigate the GSRs and the CW separately under vertical and horizontal illuminations. The geometries are as follows: $L = 300$ nm, $g = 100$ nm, $l = 370$ nm, and $w = 50$ nm. The unit cell lengths in x and y directions are $P_x = 1170$ nm and $P_y = 500$ nm, respectively, while the z span of the simulation region is 1000 nm. As expected, for vertical and horizontal polarization of the electric field,

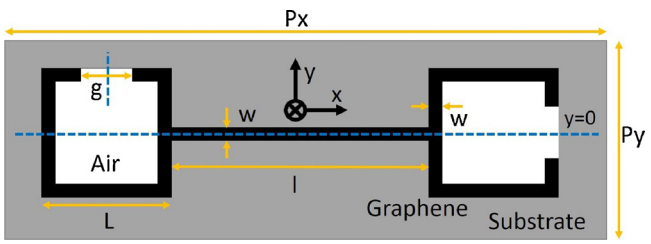

Fig. 1. Top view schematic of the unit cell of the proposed resonator. The length of the square-shaped GSR is L nm, the gap width is g nm, the CW length is l nm, and the graphene ribbon width is w nm. y = 0 is the center of the SR in the vertical direction. Unit cells of size P_x and P_y nm are arranged periodically.

the split rings have resonance responses at 3.90 and 3.68 m, respectively, at which the left and right rings are dipolar excited, respectively. The field distributions in Fig. 2(e,f) clearly show that when the gap in the lateral direction is perpendicular to the polarization direction of the electric field, resonance can be induced by the SP, while the other is forbidden. This means that the identical orthogonally distributed split rings can both act as bright resonators depending on the polarization direction of the incident electric field. For vertical illumination, the left ring is the bright resonator, while for horizontal illumination, the right one is the bright resonator. However, the CW can be fully excited only when the electric field is polarized in the strip lateral direction. As shown in Fig. 2(b), no such area is illuminated at 4.12 u*m*, where an intense dipolar oscillation is observed when the electric field is horizontally polarized (Fig. 2(c)). As a preparation, we have initially determined the resonance characteristics of the GSRs and the CW. In the next section, a detailed blueprint and a further discussion of the artificially built EIT resonator are provided.

3. Results and discussions

As the spectral responses of the SRs and the CW show strong dependence on the polarization of the incident field, we investigate them under both polarization directions. For vertical polarization, the left ring is the bright mode, while the CW and the right ring are the dark modes. The position y ($y = 0$ is the center of the SR in vertical direction) where the CW is located between the two rings is crucial to the resonance responses because the interference intensity changes with respect to it. Here, we consider three locations as examples. For y = 10 nm, as shown in Fig. 3(a), two distinct resonant dips are observed on the shoulder of the transparency window. To reveal the underlying physics, we plot the electric field amplitude distributions of the two dips and the transparency peak in Fig. 3(a1–a3). For dip (a1) shown in Fig. 3, the right branch of the left ring has a stronger resonance, and the CW is excited. Additionally, the right ring, in which the dipolar resonance was initially forbidden, now has a dipolar resonance.2

For the “a2″ dip, the left branch of the left ring shows a relatively stronger resonance, similar to the resonance in the previous section where it is only excited. However, the CW and the right ring are excited only to a smaller extent. Most surprisingly, at the transparency peak in (a3), the bright mode is not completely forbidden, and the two dark modes are excited. Hence, the field distributions here reveal that the formation mechanism is not the same as that of the classical bright-dark resonant pathway’s destructive interference in many structures. The superposition of the two resonances bridges the transparency window. To closely observe the formation of the transparency in this structure, we plot the surface current density distributions corresponding to Fig. 3 (a1–a3) in Fig. 4(a1–a3). In Fig. 4(a1), the left ring has a dipolar resonance, but the right branch intensity is stronger in accordance with the field distributions in Fig. 3(a1). The current in the CW flows toward the left ring in two directions: one into the left branch forming the destructive interference, which weakens the initial symmetric density distributions of the left ring when it is only excited; the other into the upper right branch forming the constructive interference, which enhances the initial symmetric density distributions. However, the current that flows to the right ring forms a rather symmetric dipolar resonance because the right ring is initially not excited, and no current disturbs the incoming power. With regard to the other dip, the left ring has a more symmetric current flow density distribution than that shown in Fig. 4(a1) because the current flows into the CW inversely from the two rings and destructively interferes the CW branch, which is more similar to the SR resonance described in Section 2. The current distribution at the transparency peak in Fig. 4(a3) follows that in Fig. 4(a1) but with a much weaker intensity.

When the CW is moved to y = −10 nm, the double resonance effect is eliminated because of the interference by the mutually coupled rings through the CW, and only the left ring is excited, see Fig. 3(b1). The