Role of asymmetric environment on the dark mode excitation in metamaterial analogue of electromagnetically-induced transparency

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Abstract: An otherwise dark magnetic dipole resonance in a split-ring resonator can be excited electrically with a Fano-type profile once the symmetric environment for this resonator is broken with respect to the polarized electric-field direction of incident waves. When this asymmetrically induced narrow resonance coincides with a broad dipolar resonance at an identical frequency regime, the metamaterial analogue of electromagnetically-induced transparency (EIT) window can be formed. We demonstrate that this environmental-asymmetry condition can be introduced dielectrically as well as plasmonically, either resonantly or nonresonantly, which indicates the plasmon coupling between different resonant modes is not responsible for the dark mode excitation. Thus, this result should contribute to the physical understanding on dark-mode excitation pathway for EIT-like phenomenon in plasmonic metamaterials.

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1. Introduction

Intensive interest has been shown in the past decade in the field of metamaterial analogue of various physical phenomena in traditional solid-state physics and atomic optics, such as the super-imaging [1], invisibility [2], dark hole [3], optical activity [4], nanolaser [5], and electromagnetically induced transparency (EIT) [6–12]. The EIT analogue in metamaterials was considered as a destructive interference by the plasmon coupling between two resonators with a same resonant frequency but in different metallic structures, one can resonate directly under the excitation of incident electromagnetic waves, called bright element, while the other cannot be excited by the incidence if the bright element is not presented, and thus it is a dark element. Accordingly, the dark resonator was believed to be indirectly excited at the aid of the near-field plasmon coupling. To mimic the physical mechanism for the atomic EIT phenomenon in a quantum point of view, the metamaterial version of EIT was explained in literatures as a result of the destructive interference between the excitation pathway $|0>-|1>$ and another pathway $|0>-|1>-|2>-|1>$, where $|0>-|1>$ means an excitable mode transition from the ground state $|0>$ to the excitation state $|1>$ (usually an electric dipole excitation), whereas direct mode transition $|0>-|2>$ is forbidden (i.e., state $|2>$ is a dark mode, usually a magnetic dipole resonance). Nevertheless, the dark-mode state $|2>$ can be accessed through plasmon-coupling transition $|1>-|2>$ [6,8]. In this viewpoint, a dark mode in the EIT-like phenomenon is not excited by the incident electromagnetic waves, but it is indirectly induced through the near-field plasmon coupling of a bright mode resonance [6,8,13].

To design an EIT-like metamaterial, a lot of works were devoted to the realization of a narrow dark mode (high quality factor Q) to be induced by the plasmon coupling from a broad bright mode (low Q) sharing the same resonant frequency [6,10]. Unfortunately, the important role of structural asymmetry was more or less overlooked in literatures, while the plasmon coupling is highlighted in EIT-like metamaterials. It seems interesting when a few of works found that the near-field plasmon states cannot coupled to each other unless a broken symmetry is introduced to the spatial arrangement of the bright and dark resonators [8,9], but

the underlying reason was not explained there. As a matter of fact, symmetry breaking in plasmonic nanoparticles can induce intriguing mode excitation with Fano-type response (high Q), but usually such asymmetry-introduced resonances were investigated in a background of sensing instead of plasmonic EIT [14–18]. Similarly, the additional magnetic dipole resonance, inherent to a split-ring resonator (SRR), can be pure electrically excited if the E field is polarized parallel to the gap-bearing edge [19]. All these works regarding to the structurally asymmetric excitation imply that symmetry breaking may play an important role on the dark mode excitation for the metamaterial analogue of EIT phenomenon, and thus could provide a fresh contribution to the physical understanding of this phenomenon.

   In this paper, we will demonstrate that, for the metamaterial analogue of EIT phenomenon, the dark mode is not necessary to be indirectly induced through the plasmon coupling [6–9,20], but it is actually excited by the incident electromagnetic waves due to the asymmetric near-field environment around the dark-mode element. In other words, the dark mode is no longer dark to the incident waves once its electrically symmetric environment is broken with respect to the polarized E direction. Moreover, a dielectrically asymmetric environment for the dark element is designed to manifest that the plasmon coupling between resonant states is not necessary for a dark mode excitation.
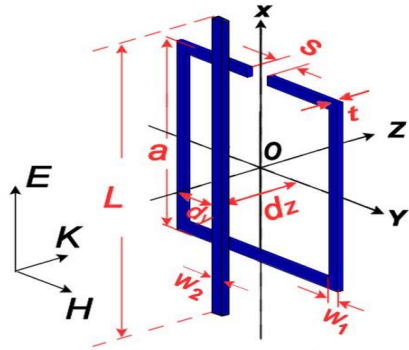

Fig. 1. (Color online) Structural schematic of the EIT-like planar metamaterial composed of the metallic SRR and wire for one unit. The SRR structure is environmentally symmetric with respect to the incident E field if $d_y = 0\,\mu m$, and environmentally asymmetric if $d_y \neq 0\,\mu m$.

2. Numerical model for the metamaterial analogue of EIT

Figure 1 shows a schematic illustration of the EIT-like metamaterial, where the geometric parameters are as follows: The edge length, width, and the split of the squared SRR are $a = 1.5\,\mu m$, $w_1 = 0.5\,\mu m$, and $s = 0.1\,\mu m$, respectively. The cut wire is in length $l = 2.76\,\mu m$ and width $w_2 = 0.25\,\mu m$, and all metallic elements are in thickness $t = 0.04\,\mu m$. The distance between the SRR and wire is $d_z = 0.32\,\mu m$ and the distance from the wire to the SRR mirror plane $o\text{-}xz$ is $d_y = 0.5\,\mu m$. The translating parameters for the SRR-wire unit are $p_x = p_y = 2.8\,\mu m$. The metallic structure is immersed in a host medium with index of refraction $n_h = 1.5$. Under the polarization situation of incident waves with electric field along the wire length and the magnetic field parallel to the SRR plane, electric dipolar oscillation in the wire is an excitable bright mode with broad absorption spectrum, whereas the magnetic dipole eigenmode with circulating current induced in the SRR is dark in absence of the wire. In our simulations, perfect electric and magnetic boundaries are used in compliance with the incident polarization configuration in Fig. 1 [21,22], and the metal is

numerically treated as silver with Drude-type permittivity ($\omega_p = 1.37 \times 10^{16} \mathrm{s}^{-1}$ and $\gamma = 8.5 \times 10^{13} \mathrm{s}^{-1}$).

3. Results and discussions

As for the scales shown in Fig. 1, both the electric dipole resonance for the cut-wire-only structure and the magnetic dipole resonance for the SRR-only structure has been designed to simultaneously locate at the frequency regime around 25 THz. Consequently, for the combined SRR-wire metamaterial in Fig. 1, different transmission spectra can be found in Figs. 2(a) and 2(b) for different configurations. It is obvious that the dark mode of magnetic dipole resonance in SRR cannot be excited for the symmetry configuration ($\mathrm{d_y} = 0\,\mu m$), where simply an electric dipole resonant dip is exhibited around 25 THz for the cut wire case [Fig. 2(a), black line]. In contrast, a narrow transparent window near 24 THz will be formed within this broad electric dipole resonant dip if the symmetric environment is broken ($\mathrm{d_y} \neq 0\,\mu m$) due to the destructive interference between the dually induced electric and magnetic dipole resonances [Fig. 2(a), red line]. From the continuous-wire case shown in Fig. 2(b), the magnetic dipole mode around 24 THz in the SRR shows the same excitation behavior. That is, it is excitable for environmentally asymmetric SRR case ($\mathrm{d_y} \neq 0\,\mu m$), while unexcitable for environmentally symmetric SRR case ($\mathrm{d_y} = 0\,\mu m$). In contrary to the usually reported dark-mode excitation by plasmon coupling between two elements resonant at a same frequency regime [6–9,20], the spectrum for the asymmetric continuous-wire case [Fig. 2(b), red line] implies that a dark mode can even be induced by a nonresonant element, since for a continuous wire its electric dipole resonance is down to zero frequency [23].
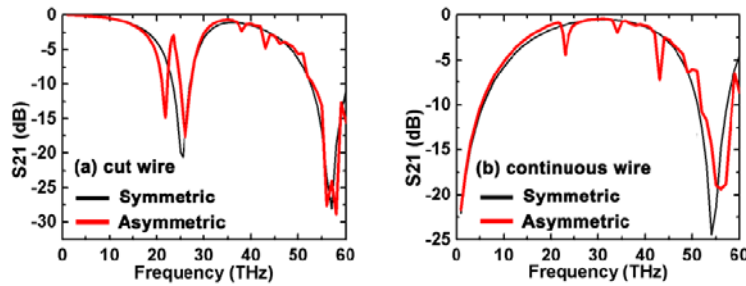

Fig. 2. (Color online) Transmission spectra for different SRR and wire configurations, where the magnetic dipole mode in SRR is around 24 THz. (a) Cut wire ($l = 2.76\mu m$) at symmetric ($\mathrm{d_y} = 0\,\mu m$) and asymmetric ($\mathrm{d_y} = 0.5\,\mu m$) positions. (b) Continuous wire ($l = \mathrm{p_x} = 2.8\mu m$) at symmetric and asymmetric positions.

Figure 2 implies the important role of the asymmetric environment in inducing an otherwise "dark" mode, the underlying physics can be understood as follows: when the balance of the electromotive force between two SRR edges parallel to the *x* direction (Fig. 1) is broken due to the asymmetrically positioned wire ($\mathrm{d_y} \neq 0\,\mu m$) in the near-field environment of SRR, a circulating surface current can be formed along the whole SRR circumference, instead of a pair of equivalent currents flowing back and forth following the polarized *E* direction. This electrically-induced circulating current resonates at the same frequency with the magnetically-excited magnetic dipole resonance in the SRR, but the former resonance exhibits a Fano-type resonant response, while the latter one shows a simple symmetric dip in the transmission spectrum. This Fano shape is actually a result of the asymmetric design of the metamaterial, and for a physical understanding it is attributed to the interference in the asymmetric structure [18]. An analytic model for the electrically coupled to

magnetic dipole resonance in Ref. 19 can be applied to this resonant excitation case due to their similarities, expect that in this work the SRR itself is symmetric with respect to the E direction, but its near-field environment does not keep balance regarding to the two SRR edges parallel to this direction. To confirm this explanation for the dark mode excitation, induced surface current distributions for symmetric and asymmetric configurations are shown in Figs. 3(a) and 3(b), respectively. The magnetic dipole resonance in the SRR is not excitable for a symmetric wire position [Fig. 3(a)], while it is excitable for an asymmetric wire position [Fig. 3(b), with circulating current distribution on the SRR surface]. Similar results in the SRR current distribution are also found for the continuous-wire case.

It should be emphasized that in literatures many proposed EIT-like metamaterials [6,8,9,11,12,20,24–26] were in fact with an asymmetric environment regarding to the polarized E field for the dark element, though its role for the dark mode excitation was not considered particularly. Note that this interpretation of inducing the dark mode by an asymmetric environment also applies to the high-order dark mode excitation in a symmetric structure proposed in Ref. 27.
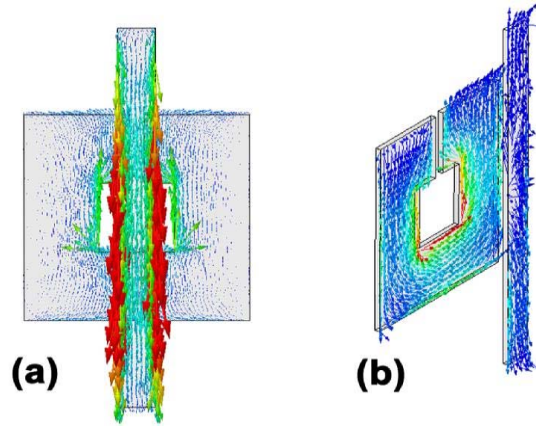

Fig. 3. (Color online) The unexcited (a) and excited (b) magnetic dipole mode of the SRR-and-cut-wire structure at 23.6 THz, for symmetric ($d_y = 0\,\mu m$, parallel currents induced nonresonantly on the left and right SRR-edge surfaces) and asymmetric ($d_y = 0.5\,\mu m$, circulating current induced resonantly on the SRR surface) environment, respectively.

To demonstrate in further that the dark mode is excited due to the unbalanced E-field environment between the two x-direction SRR edges, instead of the near-field plasmon coupling between resonant metallic elements, a dielectric slab is adopted to replace the previous metallic wire. In the simulation, this slab is deliberately positioned in a half portion of the SRR as the substrate (Fig. 4), in order to access the asymmetric-environment induced magnetic dipole resonance. With the permittivity increase of the dielectric slab, the unbalance degree of the E-field environment in the vicinity of the SRR structure increases, and thus resulting in a more pronounced magnetic dipole response [Fig. 4(a)]. Notice that a slight redshift of the magnetic dipole resonance from 21.5 THz to 18 THz will be caused with the slab permittivity ε_s increasing from 9 to 64. Because the dielectric nature of the asymmetry-introducing slab in Fig. 4(b), there is no a plasmon coupling involved in the dark mode excitation (i.e., the magnetic dipole resonance). Also, because the dielectric slab is nonresonant around this frequency regime, there is no resonant coupling necessary for the dark mode excitation. Therefore, we argue that neither the presence of a bright resonant element nor the plasmon coupling is responsible for the dark mode excitation. In contrary, what ultimately induces the dark mode resonance should be the asymmetric near-field environment, with respect to the incident E polarization direction, around the "dark" element.
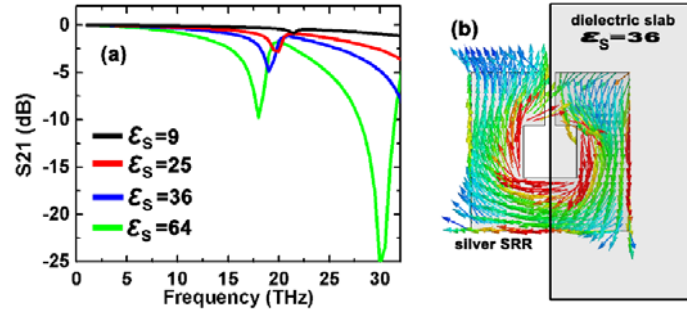
Fig. 4. (Color online) Magnetic dipole resonance induced in the SRR structure due to the asymmetric environment at presence of the continuous dielectric slab. (a) Slab permittivity ε_s dependence of the magnetic dipole resonance. (b) The current map of the magnetic dipole resonance induced on the metallic SRR surface. Note that no magnetic dipole resonance can be excited, regardless of the slab permittivity, if the dielectric slab is positioned in the middle place regarding to the SRR.

4. Summary

In summary, we numerically investigate the excitation manner for the dark mode of magnetic dipole resonance inherent to the SRR, with a particular attention on the role of the asymmetric near-field environment around the SRR. The results indicate that, for the metamaterial analogue of the atomic EIT phenomenon, whether or not a dark mode can be excited does not rely on the plasmon coupling from a bright mode resonance, but it depends on the near-field environment around the "dark" SRR element. The dark mode excitation can be accessed as soon as a symmetry-broken environment is presented with respect to the incident E polarization direction, no matter this asymmetry is introduced resonantly or nonresonantly, dielectrically or plasmonically. Our results presented in this work should contribute to a fresh understanding of the dark mode excitation in the metamaterial analogue of the atomic EIT phenomenon. Nevertheless, it should be mentioned in passing that, though plasmon coupling is not necessary to induce a dark mode, it does play an important role on the bright-and-dark mode coupling in EIT-like plasmonic metamaterials. Specifically, Asymmetry awakes the dark mode excitation, and then the "dark" mode interacts with a bright mode through the plasmon coupling in a manner of destructive interference. Therefore, the plasmon-assisted interaction and localized asymmetry should work in tandem to produce the EIT-like phenomenon in metamaterials.