Plasmonically induced transparent magnetic resonance in a metallic metamaterial composed of asymmetric double bars

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Abstract: We demonstrate that the trapped magnetic resonance mode can be induced in an asymmetric double-bar structure for electromagnetic waves normally incident onto the double-bar plane, which mode otherwise cannot be excited if the double bars are equal in length. By adjusting the structural geometry, the trapped magnetic resonance becomes transparent with little resonance absorption when it happens in the dipolar resonance regime, a phenomenon so-called plasmonic analogue of electromagnetically induced transparency (EIT). This planar EIT-like metamaterial offers a great geometry simplification by combining the radiant and subradiant resonant modes in a single double-bar resonator.

OCIS codes: (160.3918) Metamaterials; (250.5403) Plasmonics.

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1. Introduction

For conventional metamaterials, the spatial distances between discrete elements were generally out of the touch of neighboring near fields localized around individual elements, and consequently the plasmonic interactions of nearby metal structures could be neglected. Though this treatment was feasible to study the average effect in terms of the effective medium approximation (such as left-handed metamaterials), it is not applicable to interparticle-coupled metamaterials, for which great interest has been provoked recently because the plasmon coupling between adjacent metallic elements can induce many attractive electromagnetic properties [1–3]. For example, the plasmon hybridization in neighboring elements can split the resonant spectrum and obtain a great optical activity [4], while the plasmonic analogue of electromagnetically induced transparency (EIT) in metamaterials, usually composed of dual resonators [5–11], is a result of plasmon coupling between a radiative eigenmode (e.g., dipolar resonance) in one resonator and a subradiant eigenmode (e.g., quadrupolar resonance) in the adjacent resonator in a manner of destructive interference.

Generally, intriguing properties in coupled metamaterials are resulted from various plasmon coupling configurations with either structural symmetry or asymmetry. A straight configuration is to squeeze the element interval and thus the near-field coupling can be significantly enhanced between metal elements, including those symmetric elements equivalent in both metal shape and spatial arrangement [12]. In contrast, spatially and/or structurally asymmetric configurations usually take an astonishing role in modifying the electromagnetic responses in coupled metamaterials. Spatially asymmetric coupling, i.e., rotating or translating the neighboring homomorphic elements with respect to one another can lead to optical activity or additional dark-mode excitation, respectively [4,13]. On the other hand, structurally asymmetric coupling happens by deliberately breaking the element symmetry in shape as well as in size, such as concentric double rings [14,15], ring-disk composite [16], asymmetric split-ring pairs [17,18], and mismatched nanoparticle pairs [19]. A common coupling characteristic for such size or shape asymmetry in adjacent elements is the Fano-type resonance with a transmission dip closely accompanied with a transmission peak [14–18,20]. In this work, we numerically demonstrate that a trapped magnetic/quadrupolar resonance with Fano-type profile is excitable by introducing asymmetry in a double-bar structure. A plasmonically induced transparency can be obtained when this trapped magnetic resonance coincides with a dipolar resonance. It is emphasized that this planar design based on a simple double-bar structure takes a great convenience for experimental treatment in comparison with various EIT-like metamaterials studied in literatures [5–11], which are usually either in three dimensions or with complex planar geometry.

2. Plasmonic metamaterial and numerical model

Figure 1 shows a schematic illustration of the metallic metamaterial and the polarization of incident light. The bar geometry with length $\mathrm{l} = 200\,nm$, width $\mathrm{w} = 30\,nm$, thinckness $\mathrm{t} = 30\,nm$, and the gap between double bars is $\mathrm{g} = 30\,nm$. The translating parameters for the double bars are: $\mathrm{p}_x = 250\,nm$, $\mathrm{p}_y = 600\,nm$, and $\mathrm{p}_z = 100\,nm$. The substrate is quartz with index of refraction $\mathrm{n}_s = 1.55$, and the metallic structure is immerged in a host medium with index of refraction $\mathrm{n}_h = 1.94$. Under the polarization situation of incident waves with electric field along the bar length, dipolar oscillation is an excitable bright mode, whereas the quadrupolar eigenmode with antiparallel induced currents inherent to the double parallel bars is subradiant/dark because the double bars are electrically equivalent for their same lengths. In our simulations [21,22], perfect electric and magnetic boundaries are used in compliance with the incident polarization configuration, and the metal is defined by using Drude dispersion with $\omega_p = 1.37\times10^{16}\,s^{-1}$ and $\gamma = 1.2\times10^{14}\,s^{-1}$, where γ is three times of the theoretical bulk value in order to account for nanofabrication tolerances [7,8].

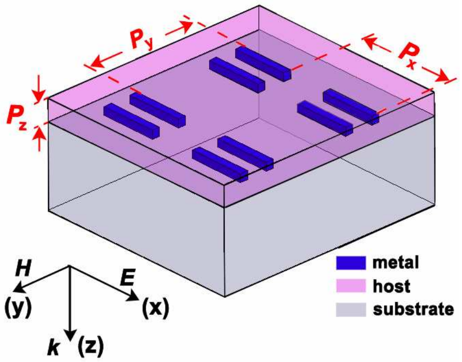

Fig. 1. (Color online) Structural schematic of the metallic double-bar metamaterial. Only a single double-bar layer in the propagation direction is considered in simulations.

3. Results and discussions

Figures 2(a) and 2(b) show the calculated transmission spectra for the symmetric double-bar structure with equal bar lengths $\mathrm{l} = 200\,nm$ and $120\,nm$, respectively. It is found that dipolar resonances occur near $\mathrm{f}_1 = 162\,THz$ and $\mathrm{f}_2 = 248\,THz$, respectively. As is known, the asymmetric mode (i.e., the quadrupolar resonant mode with antiparallel induced current at the surface of the double-bar structure) cannot be excited magnetically since the magnetic field component is parallel to the double-bar plane, also it cannot be excited electrically because the symmetric double bars (i.e., bars in the same length) are equivalent with respect to the polarized electric field. However, by breaking the length symmetry of the double bars, e.g., keeping the length of one of the double bars as $\mathrm{l} = 200\,nm$ while shortening the length of

#131817 - $15.00 USD Received 16 Jul 2010; revised 4 Aug 2010; accepted 4 Aug 2010; published 9 Aug 2010

another bar to be $l' = 120\,nm$, a third resonant mode, in addition to these two dipolar resonances as presented in Figs. 2(a) and 2(b), can be induced around $f_3 = 202\,THz$ with a Fano-type transmission spectrum [Fig. 2(c)]. This additional mode confines a strong intensity of magnetic field in the gap of the asymmetric double bars, and thus is a nonradiative/trapped magnetic resonance with antiparallel induced currents on the double bar surfaces. To confirm these dipolar and quadrupolar modes, magnetic field distributions are presented in Figs. 2(d)–2(h), corresponding to five resonances in Figs. 2(a)–2(c), respectively.

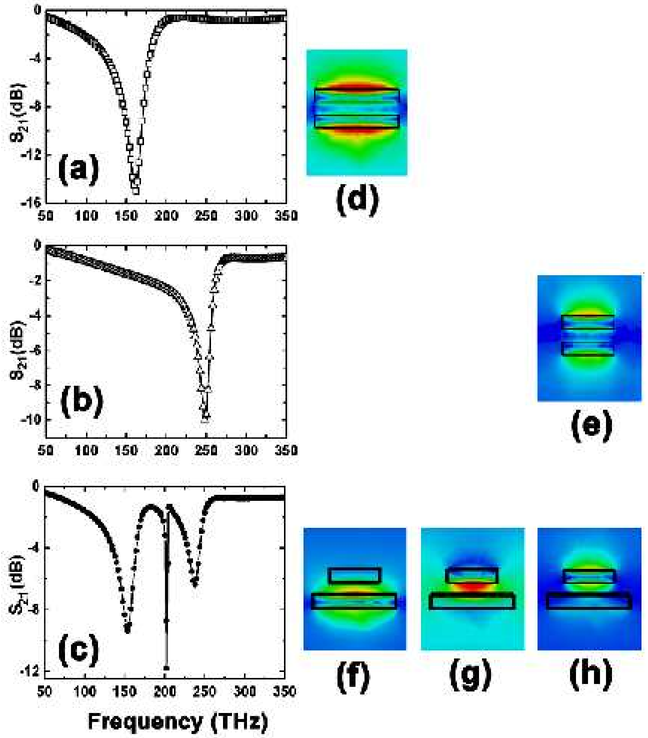

Fig. 2. (Color online) Transmission spectra of the double-bar metamaterial with (a) symmetric bar lengths $l = l' = 200\,nm$, (b) symmetric bar lengths $l = l' = 120\,nm$, and (c) asymmetric bar lengths $l = 200\,nm$ and $l' = 120\,nm$. Magnetic field distributions for five resonances in (a)-(c) are shown in the right panel (d)-(h), respectively.

The additional magnetic resonance is induced electrically since the asymmetric double-rod structure is not equivalent with respect to the polarized electric field of the incident light, and it is physically similar to the electrically excited magnetic resonance in split-ring resonators [23]. Nevertheless, it should be of interest that a plasmon version of the EIT phenomenon can be obtained in this asymmetric double-bar metamaterial, if structural parameters are adjusted to make the trapped magnetic resonance locate within the frequency regime of the dipolar resonance. As shown in Fig. 3, when the dipolar and quadrupolar resonances coincide, the latter one will become transparent around 200 THz. In different to the EIT phenomenon in an atomic system, the intrinsic metal loss in the metamaterial cannot be eliminated at the optical spectrum [7]. This transparency window, as well as the corresponding narrow dip at the middle portion of the dipolar absorption profile, is a result of the destructive interference between the two excitation pathways, namely, direct excitation of the radiative dipolar plasmon oscillation and indirect excitation of the nonradiative quadrupolar plasmon oscillation [5,7].

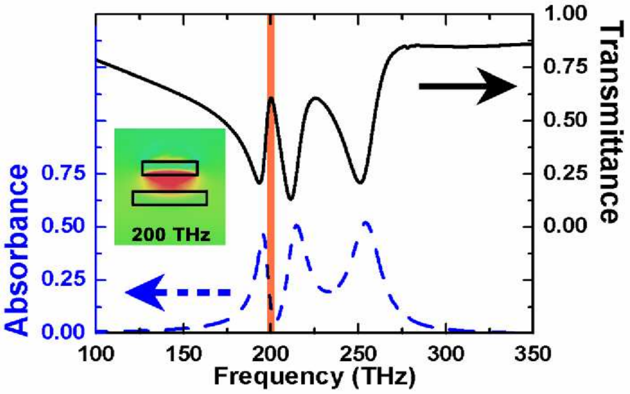

Fig. 3. (Color online) EIT-like transmittance and absorbance in the asymmetric double-bar metamaterial with some adjusted structural scales as follows: $l = 157\ nm$, $l' = 117\ nm$, $g = 40\ nm$, $P_x = 240\ nm$, and $P_y = 590\ nm$. The orange vertical shadow indicates the position of the transparency window and absorption dip, while the inset presents the localized magnetic field distribution for the transparency window.

According to the interpretation for a plasmonic analogue of EIT phenomenon [4–8], the incident waves excite the dipolar plasmon state, and then this excited dipolar oscillation plasmonically couples to the quadrupolar oscillation. Transparency window would be formed if there is a destructive interference between the direct excitation pathway of dipolar plasmon oscillation and the indirect excitation pathway of quadrupolar plasmon oscillation. During this process, radiative plasmon state transfers the exciting electromagnetic resonance to the subradiant plasmon state through the aid of near-field plasmon coupling. Note that this plasmon coupling in EIT-like metamaterials happens at a same resonance frequency of two different resonant modes [5–11]. In contrast, the optical nonlinearity is inherent in an atomic EIT system where a control light is different to a probe light in frequency [24,25]. Here, the plasmon coupling in a manner of destructive interference acts as the control factor which determines the absorption or transparency of the probe/incident light. If the plasmon coupling does not exist for these two resonant modes, there should be a resonant dip (absorption) in the transmission spectrum, instead of an EIT-like resonant transparency, as presented in Fig. 2(c). Notice that the EIT-like peak can never be obtained in the double-bar structure unless a structural asymmetry will be introduced. Moreover, the occurrence of EIT not only depends on the bar scales and the bar-bar gap, but it also depends on the periodic array intervals. The latter dependence should imply the importance of the ordered arrangement on the EIT occurrence. In fact, since such transparency window in EIT-like characteristic is a result of destructive interference between dark and bright resonances, any disorder in the structural arrangement, or even fabrication imperfections of element size and position, will break or disturb the coherent coupling between elements, and thus is not preferred for a significant EIT-like window.

Another characteristic of EIT-like resonance in metamaterials is the large group index that is useful for slowing down the electromagnetic propagation in nanoplasmonic devices. To characterize this property for the EIT-like transmission peak in the asymmetric double-bar metamaterial as presented in Fig. 3, the group index dispersion is calculated. It is found that the maximum group index can reach a value of 27 at the transparency window (Fig. 4, red solid line). Note that a loss factor $\gamma = 1.2\times10^{14}\,s^{-1}$, triple the bulk value of gold, has been considered for the simulation. If the bulk value $\gamma_{bulk} = 4.08\times10^{13}\,s^{-1}$ is used for the gold in the Drude formula, the maximum value of the group index can reach a value as large as 62 (Fig. 4, black circle line). This difference in the maximum value of the group index indicates how much it can be affected by the metal loss factor in the Drude formula. Interestingly,

#131817 - $15.00 USD Received 16 Jul 2010; revised 4 Aug 2010; accepted 4 Aug 2010; published 9 Aug 2010

negative group index can be found in the dipolar resonance regime, this is known as superluminal wave propagation, a common characteristic to lossy metamaterials [26], and was experimentally observed in atomic EIT systems [27,28].

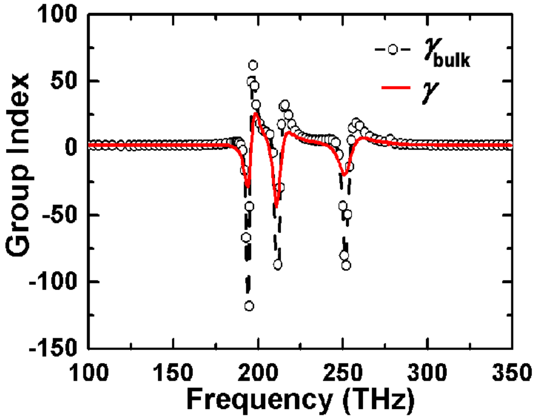

Fig. 4. (Color online) Group index of the EIT-like asymmetric double-bar metamaterial with structural parameters as presented in Fig. 3. The bulk value of the loss factor γ_{bulk} (circle line) is considered to evaluate the influence of the metal damping constant on the group index.

4. Summary

In summary, in addition to the dipolar resonant mode, an electrically excited quadrupolar mode with Fano-type profile can be induced in a metallic double-bar metamaterial by breaking the length symmetry. The radiative dipolar plasmon oscillation cannot only absorb the polarized light, but also it can interact destructively with the subradiant quadrupolar mode through the near-field plasmon coupling. Consequently, a transparency resonance can be obtained instead of an absorption one due to destructive interference between these two resonant modes. It is emphasized that this asymmetric double-bar structure is currently the most simplified EIT-like metamaterial by combining the radiant and subradiant resonant modes in a single double-bar resonator, and thus would take great convenience for future experimental study of plasmonic EIT phenomenon.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 10874081, No. 10904012, and No. 60990320), the National Key Projects for Basic Researches of China (No. 2010CB630703), and the Research Fund for the Doctoral Program of Higher Education of China (No. 20090092120031).