Plasmon-induced absorption in stacked metamaterials based on phase retardation*

Wan Ming-Li(万明理)[a)†], Yuan Shu-Qing(袁书卿)[a)], Dai Ke-Jie(代克杰)[b)], Song Yue-Li(宋月丽)[a)], Zhou Feng-Qun(周丰群)[a)], and He Jin-Na(何金娜)[a)]

[a)] *Electric and Information Engineering College, Pingdingshan University, Pingdingshan* 467000, *China*

[b)] *High-Voltage Intelligent Switch Engineering Research Center, Pingdingshan University, Pingdingshan* 467000, *China*

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In this paper, based on the constructive interference of plasmonic dipolar and quadrupolar modes, a classical analogue of electromagnetically induced absorption (EIA) is demonstrated theoretically in a stacked metamaterial consisting of a short metal strip (which acts as a bright resonator) and a long metal strip (acting as a dark resonator), which has been reported to support the electromagnetically induced transparency (EIT) effect. The transition from EIA to EIT can be clearly observed in the absorbance spectra via varying the vertical spacing between two resonant oscillators. With the help of the coupled two-oscillator model, the phase shift between the bright and dark resonance modes is calculated by fitting the simulated absorbance spectra, which reveals the physical mechanisms behind constructive and destructive interference effects in EIT/EIA metamaterials.

Keywords: metamaterial, electromagnetically induced transparency, electromagnetically induced absorption, phase retardation

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1. Introduction

Electromagnetically induced transparency (EIT) is a quantum interference phenomenon which generally occurs in a three-level atomic system and renders the medium transparent in a narrow transmission window. This effect markedly modifies the dispersive properties of the medium, which can lead to dramatic reduction in group velocity and enhancement of nonlinear interactions.[1] In recent years, analogues of the EIT-like behavior in classical systems such as microresonators,[2] photonic crystals,[3] electric circuits,[4] and in particular the plasmonic systems,[5–13] have attracted much attention. The plasmonic analogue of EIT based on a metamaterial structure is a result of the destructive interference of the two different excitation routes of plasmonic resonant modes, where the bright mode ($|B\rangle$) can be excited by two pathways: $|I\rangle \rightarrow |B\rangle$ and $|I\rangle \rightarrow |B\rangle \rightarrow |D\rangle \rightarrow |B\rangle$, with the symbols $|I\rangle$ and $|D\rangle$ representing the incident light and the dark mode, respectively.[5,9–11] On the contrary, when both pathways constructively interact with each other, the narrow dip in the absorbance spectrum for the EIT-like effect can be substituted by a sharp absorption peak, which is called electromagnetically induced absorption (EIA).

EIA behavior in atomic physics was first demonstrated by Akulshin *et al.*[14] However, so far only a few studies have concerned the plasmonic analogue of EIA in metamaterials.[15,16] In 2012, Taubert *et al.*[15] provided the first experimental demonstration of the EIA-like effect in optical metamaterials by employing the benefits of near-field coupling on the one hand and phase retardation effects due to far-field coupling on the other hand. Subsequently, Tassin *et al.*[16] developed a theoretical model based on two radiating micro-oscillators to investigate the EIA and EIT effects in planar metamaterials. Due to its narrow spectral characteristics, EIA in metamaterials possesses promising potential applications in nonlinear optics.

In this paper, a plasmonic analogue of the EIA effect is demonstrated theoretically in a stacked metallic nanostructure consisting of an upper short strip and a lower elongated strip. The upper gold strip functions as an optical antenna, in a radiative role, and the lower elongated one supports high-order multipolar plasmon resonances, thus acting in a sub-radiative role. The constructive interference between them gives rise to the EIA effect. Interestingly, the EIA spectral response can be tuned gradually to the EIT effect by changing the vertical spacing between these two strips, which is demonstrated by the phase shift obtained by solving the coupled two-oscillator model. This work clearly demonstrates the physical mechanism behind these two interference effects.

2. Structures and simulation method

Figure 1 displays the schematics of the metallic metamaterial and the polarization of the incident light of interest. The short metallic strip is stacked on the long metallic one with a vertical spacing D_z. The lateral displacement

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†Corresponding author. E-mail: mlwan@pdsu.edu.cn

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of the top short strip with respect to the symmetry axis of the underlying long strip is denoted as S. This structure is radiated normally by a planar electromagnetic wave with an electric field along the short strip. All numerical calculations are carried out by solving Maxwell equations based on the finite element method (FEM). In our simulation configuration, perfect electric and magnetic boundaries are used in the x and y directions in compliance with the incident polarization. Gold is selected as the metallic material due to its low intrinsic loss in the infrared spectral region. The permittivity of gold is described by the Drude model with the plasma frequency $\omega_p = 1.366 \times 10^{16}$ rad/s and the damping constant $\gamma = 1.225 \times 10^{14}$ 1/s, which is three times that of the bulk gold due to the surface scattering and grain boundary effects in the thin film.[5,17] In order to simplify the calculation process, the ambient medium is assumed to be air.

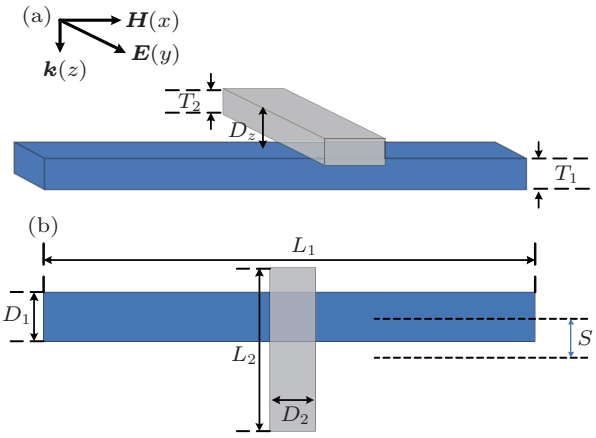


Fig. 1. (color online) Schematic diagrams of the stacked structure and the incident light polarization, where panels (a) and (b) show the oblique view and top view, respectively. In all simulations, the periodicity is set to be 850 nm in both the x and y directions.

3. Results and discussion

As is well known, plasmonic systems have inherently broader resonant linewidths than typical atomic oscillators, and the difference in linewidth between bright and dark plasmonic modes is not so pronounced as that of atoms. Thus, it is advisable to choose a somewhat large detuning of the spectral resonance positions of the bright dipolar and the dark high-order plasmonic modes to exhibit double peaks in the absorbance spectra for the observability of the EIA phenomena.[15] As a result, the geometrical parameters of these two strips are optimized to be $L_1 \times D_1 \times T_1 = 770$ nm$\times$60 nm$\times$40 nm and $L_2 \times D_2 \times T_2 = 360$ nm$\times$80 nm$\times$40 nm.

Figures 2(a) and 2(b) show the simulated transmission and absorption spectra for the structures with the values of lateral displacement S of 0 nm and 40 nm, respectively. The absorbance is calculated using the formula $A = 1 - T - R$, where T and R denote the transmittance and reflectance respectively. In the absence of structural asymmetry, that is, for $S = 0$ nm, there is only a single resonance in the absorbance or transmittance spectrum, which should be attributed to the excitation of the dipole resonance inside the upper strip. Once the structural symmetry is destroyed by introducing the lateral offset S, the near-field coupling between these two resonators may start. As in the case of $S = 40$ nm, there appears a frequency window with a small transmission in the transmittance spectrum, which looks like the spectral shape in EIT systems. However, an added high absorption peak around 270 THz (indicated by triangle for $S = 40$ nm in Fig. 2(b)) emerges above the original broad absorbance curve that is a distinctive signature in contrast to that of EIT-like features. Compared with the radiative mode at 253 THz (indicated by the inverted triangle for $S = 40$ nm in Fig. 2(b)), the resonance at 270 THz has a narrow, subdipolar linewidth much smaller than that of the dipolar

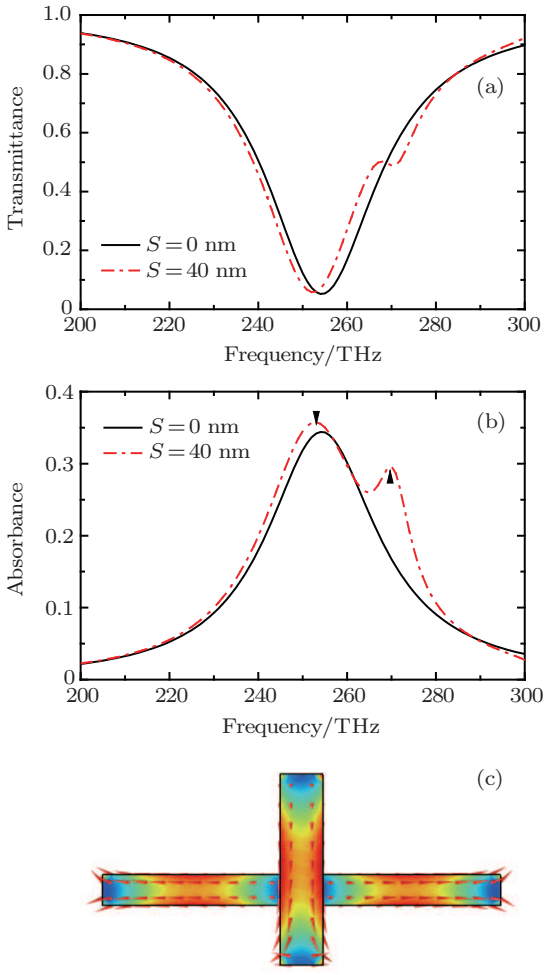


Fig. 2. (color online) Transmittance (a) and absorbance (b) spectra of EIA nanostructures for symmetric structure $S = 0$ nm and asymmetric structure $S = 40$ nm. The geometrical parameters are $L_1 \times D_1 \times T_1 = 770$ mm$\times$60 mm$\times$40 nm, $L_2 \times D_2 \times T_2 = 360$ nm$\times$80 $\times$ 40 nm, and $D_z = 120$ nm. Owing to plasmon hybridization between dipolar and quadrupolar modes, there is a slight spectral shift between the two resonant peak positions. (c) Current density distributions in both strips at the resonance marked by the triangle for $S = 40$ nm in Fig. 2(b). The arrows represent the oscillatory directions of currents.

antenna, which is attributed to the excitation of a dark quadrupolar plasmon mode in the long strip. We explain the above phenomenon in terms of plasmonic EIA, originating from the constructive interference of the dipole mode in the short strip and the quadrupolar mode in the long strip.[14,15]

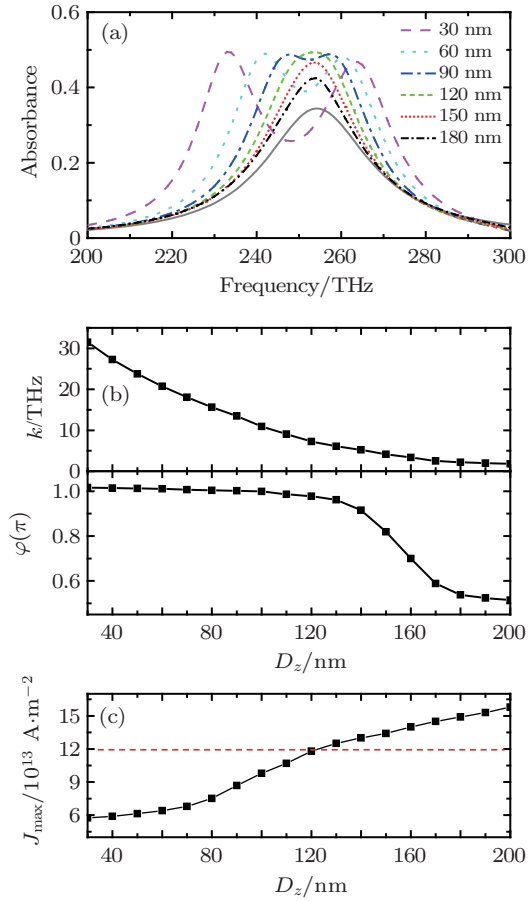


Fig. 3. (color online) (a) Calculated absorbance spectra of the three-dimensional plasmonic nanosturcture with vertical distance $D_z = 0$, 30, 60, 90, 120, 150, 180 nm and lateral displacement $S = 60$ nm. The absorbance curve (solid line) of the symmetric structure is shown for comparison. In order to reduce the detuning δ, the geometrical parameters are tailored to $L_1 \times D_1 \times T_1 = 770$ nm×40 nm×40 nm and $L_2 \times D_2 \times T_2 = 360$ nm×80 nm×40 nm. (b) Extracted coupling parameters each as a function of vertical distance. The offset D_z ranges from 30 nm to 200 nm in steps of 10 nm to obtain smooth curves. Values of κ and φ are obtained by fitting Eq. (3) to the absorbance curves, part of which is presented in Fig. 3(a). (c) Maximum current density value (J_{max}) in the upper strip at the dark resonant position as a function of D_z.

In order to explore the origin of the spectral shape, the current densities inside two antennas at the quadrupolar resonant peak are shown in Fig. 2(c). From the figure, we can clearly see that there exist two opposite oscillatory currents on both sides of the lower strip, which firmly support the occurrence of sub-radiative resonance from quadrupolar plasmon. Meanwhile, the quadrupolar plasmon interferes constructively with the dipolar plasmon to cause the tremendous polarization of the dipolar antenna.[15] Owing to this constructive interference between bright and dark oscillators, the absorbance at 270 THz has a huge enhancement compared with the uncoupled case, which corresponds to an enhancement factor of about 2.

Compared with the geometrical sizes of the EIT system in Ref. [18], most parameters are similar except the vertical distance between the upper strip and the lower strip. In order to clearly exhibit the influence of the vertical distance on the spectral response for the metamaterial of interest, the structural parameters are re-designed to ensure that the resonant frequency of the bright mode is equal to that of the dark one and the corresponding absorbance spectra each as a function of the spacing D_z are calculated and plotted in Fig. 3(a). With the value of D_z increasing, the spectra with EIT-like features change qualitatively into EIA-like spectral shapes in the absorbance spectra. In comparison with the asymmetric double resonances shown in Fig. 2(b), the absorbance spectra exhibit Lorentzian-like spectral shapes since the detuning δ between dipolar and quadrupolar modes is tuned to approximately 1.6 THz. In addition, the absorbance spectrum of the symmetric structure ($S = 0$ nm) is also provided for comparison (see the solid line). The obviously enhanced absorption for the asymmetric structure further indicates the occurrence of an EIA-like effect.

In order to make an in-depth elucidation of the physical mechanism under the transformation between EIA and EIT, a two-coupled-oscillator model is constructed to analyze the EIA/EIT systems.[5,15] The upper strip in our structure is denoted as oscillator 1 with charges $q_1(t)$ and resonance frequency ω_0, which is driven by incident light $E(t)$. The underlying strip is denoted as oscillator 2 with charges $q_2(t)$ and resonance $\omega_0 + \delta$, which is excited only by oscillator 1 through the near-field coupling between two oscillators, described by the complex coupling coefficient $\kappa^* \exp(\mathrm{j}\varphi)$, where φ represents the phase shift due to the coupling distance in the propagation direction of incident light. This model can be represented by the following two differential equations:

$$\ddot{q}_1(t) + \gamma_1 \dot{q}_1(t) + \omega_0^2 q_1(t) + \kappa \exp(\mathrm{j}\varphi)\dot{q}_2(t) = E(t), \quad (1)$$

$$\ddot{q}_2(t) + \gamma_2 \dot{q}_2(t) + (\omega_0 + \delta)^2 q_2(t) + \kappa \exp(\mathrm{j}\varphi)\dot{q}_1(t) = 0. \quad (2)$$

Here the γ_1 and γ_2 describe the linewidths in oscillators 1 and 2, respectively. After solving Eqs. (1) and (2) with the approximation $\omega_0^2 - \omega^2 \approx -2\omega_0(\omega - \omega_0)$, the absorbance as a function of frequency can be obtained as follows:

$$A(\omega) = \mathrm{Im}\frac{f(\omega - \omega_0 - \delta + \mathrm{j}\gamma_2/2)}{\kappa^2 \exp(2\mathrm{j}\varphi) - 4(\omega - \omega_0 + \mathrm{j}\gamma_1/2)(\omega - \omega_0 - \delta + \mathrm{j}\gamma_2/2)}. \quad (3)$$

By fitting the calculated absorbance curves using Eq. (3), the coupling amplitude κ and phase shift φ are obtained and presented in Fig. 3(b). When the vertical distance D_z is not greater than 120 nm, owing to the quasi-electrostatic near-field effect, the dipolar plasmon in the bright antenna excites the quadrupolar plasmon in the dark antenna and then in turn the latter excites the former again. The phase shift in the entire process is approximately π so that the two excitation pathways interfere destructively and form a transparent window in the transmittance region as well as a sharp dip in the absorbance spectrum.[10] When the interactive distance between two antennas increases, the coupling strength κ weakens, causing the dip to become smaller and smaller, and to completely vanish at $D_z = 120$ nm. As the spacing D_z exceeds 120 nm in an intermediate region, the near-field coupling is still effective since the coupling strength continues to lessen. Meanwhile, the far-field effect plays an important role.[15] As a result, the coupling between bright and dark antennas changes from a destructive interaction into a constructive interaction, resulting in an enhanced absorbance in oscillator 1. When further increasing the spacing D_z, the near-field coupling becomes more and more weak, which makes the dark mode unable to be excited at all, and the absorbance spectrum evolves into a dipolar lineshape.

In the EIT effect, the polarization in the bright antenna is cancelled by the dark mode, but the scenario is reversed in the EIA effect. We evaluate the maximum current density value ($J_{\max}$) at the dark resonant position, as a function of D_z in the upper strip, and the results are shown in Fig. 3(c). The dashed line corresponds to the maximum current density value J_{120} for the case of vertical distance $D_z = 120$ nm. In a spacing region from 30 nm to 200 nm, $J_{\max}$ increases monotonically and exceeds J_{120} at the spacing D_z = 130 nm. For the cases where the vertical spacing is not greater than 120 nm, a monotonic increase of current density arises from the weakening of the coupling strength κ; when D_z is greater than 120 nm, although κ still decreases, the reduction of the phase shift strengthens the constructive interference between the bright and dark modes, and the resulting effect is that the current in the upper strip still increases. The variation of the maximum current density value with vertical spacing D_z is well consistent with the results obtained above.

4. Conclusions

In this paper, an EIA-like feature in the absorbance spectrum can be clearly observed for a layered plasmonic metamaterial by constructively coupling the dipolar mode of the short strip to the quadrupolar mode of the long strip. The transformation from the EIT effect to the EIA effect reveals that phase retardation can be manipulated by changing the spacing between the oscillators, which offers a means for useful applications in phase control for plasmonic coupling.

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