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The respective effects of direct and indirect couplings on the plasmon-induced transparency in waveguide systems

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ABSTRACT

We investigate respectively the effects of direct and indirect couplings on electromagnetically induced transparency (EIT)-like in a Metal–Insulator–Metal (MIM) bus waveguide coupled to two aperture-resonators (ARS). Adjusting the intensity of direct and indirect couplings, we can intentionally realize, modulate and eliminate the EIT-like transmission in the proposed plasmonic structures. The consistency between theoretical results and finite-difference time-domain (FDTD) simulations indicates that the direct coupling can give rise to EIT-like phenomenon in symmetrical structure. Moreover, the EIT-like transmission dips can be shifted back to the original resonant frequency when the two couplings offset each other. These results may provide a helpful guideline for the control of light in highly integrated optical circuits.

1. Introduction

Electromagnetically induced transparency (EIT) occurs in atomic systems is attributed to the quantum interference between the excitation pathways to atomic upper levels [1–3]. Due to the strong dispersion and slow-light propagation within the transparency window, EIT promises a variety of potential applications in the fields of slow light effects [4–6] and integrated photonic devices [7,8]. However, the strict experimental conditions on the realization of EIT restrict its practical applications. Thus, many researchers have made great efforts in mimicking EIT in classical structures [9,10]. A variety of classical configurations have been investigated such as coupled dielectric resonators [11,12], metamaterial [13–15], EIT-like effect in split-ring resonators [16,17] and phase-coupled PIT [18,19]. Among the different plasmonic structures, Metal–Insulator–Metal (MIM) plasmonic waveguides, which support modes with deep wavelength scale and own an acceptable length for surface plasmon polaritons (SPPs) propagation, have attracted considerable attention.

In view of the unique features of MIM waveguide, the plasmonic analog of EIT observed in the plasmonic waveguide systems has been theoretically predicted [19–31] and experimentally illustrated [32,33]. Li and co-workers, using the temporal coupled mode theory (CMT), theoretically analyzed mode-splitting for both directly and indirectly coupled cavity systems [31]. Based on CMT, Lu and co-workers demonstrated analog of EIT in multi-nanoresonator-coupled waveguide systems [19]. Further, a uniform theoretical model was established to study PIT in the plasmonic stub waveguide [30]. However, in the process of realizing and modulating EIT-like transmission, very few works investigate dividually the effects of direct and indirect coupling on EIT-like transmission.

In this letter, we investigate respectively the effects of direct and indirect couplings on EIT-like spectral features in a plasmonic waveguide system, which consists of an MIM bus waveguide and two side-coupled aperture-resonators (ARS). By fixing the coupling distance L, we theoretically and numerically exhibit EIT-like phenomena induced by direct coupling in the symmetrical structure. Moreover, by fixing the direct coupling coefficient μ, we analyze the effect of indirect coupling on EIT-like spectra for both symmetrical and asymmetrical structures. It is found that the PIT transmission dips can shift back to the original resonant frequency when the two couplings offset each other. In particular, the offset can lead to the elimination of EIT-like phenomenon in symmetrical system. Besides, the slow-light effect is also investigated. Hence, the EIT-like spectra can be intentionally achieved, modulated and eliminated by modulating the direct and indirect couplings in our plasmonic waveguide structure.

2. Structure and theory model

Fig. 1 is a schematic illustration of the proposed two-dimensional (2D) plasmonic waveguide system which consists of an MIM

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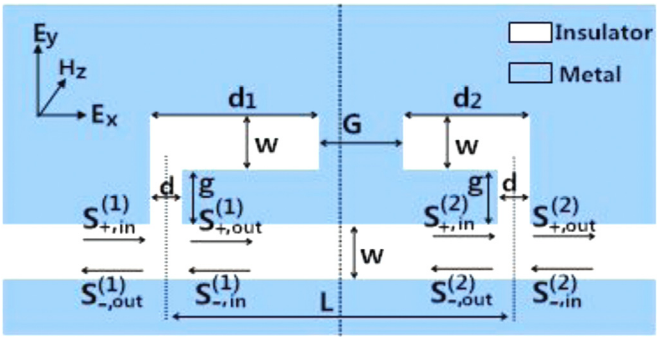

Fig. 1. Schematic illustration of 2D MIM waveguide system coupled to two ARS.

bus waveguide coupled to two ARS. The metal and insulator are selected as gold and air, respectively. The frequency dependent permittivity of the gold is approximated by the Drude model, which defines as $\varepsilon(\omega)=1-{\omega_p}^2/(\omega^2+i\omega\gamma_p)$, with the plasma frequency $\omega_p=1.37\times10^{16}$ Hz and the absorption coefficient $\gamma_p=4.08\times10^{13}$ Hz. These parameters are obtained by fitting the experimental results [34]. The width w for both the bus waveguide and the resonators is 50 nm. The length and width of the insulator aperture are selected as $g=50$ nm and $d=20$ nm, respectively. These structural parameters are fixed throughout the paper. The other structure parameters are gold gap distance between the two ARS (G), lengths of the two ARS (d_1 and d_2), and the coupling distance between the two ARS (L). A computational window of $Lx\times Ly=2000\times1800$ nm^2 was set to simulate the structure, where the structure in the z direction is infinite. The 2D Finite difference time domain (FDTD) method with the perfect matched layer (PML) boundary condition was used to simulate the transmission characteristics, the spatial mesh steps were set as $\Delta x=\Delta y=5$ nm and the time step was set as $\Delta t=\Delta x/2c$ (c is the velocity of light in the vacuum). When the TM-polarized light is injected along the x-axis, the SPP waves can be formed on the metal–insulator interfaces and can be confined in the MIM bus waveguide.

As the SPP waves pass through the bus waveguide, the energy can be coupled into the resonators through the insulator aperture and the dynamic transmission characteristics of the proposed structure can be described by the CMT [19,31,35]. As shown in Fig. 1, $S^{(i)}_{p,in}$ and $S^{(i)}_{p,out}$ stand for the incoming and outgoing waves into the ith resonator. The subscripts $p=\pm$ represent the two propagating directions of waves, as depicted in Fig. 1. Based on the CMT [19,31,35], the energy amplitude a_i of the ith resonator ($i=1$, 2) can be expressed as

$$\frac{da_i}{dt}=\left(-j\omega_i-\frac{1}{\tau_{0,i}}-\frac{1}{\tau_{e,i}}\right)a_i+\sqrt{\frac{1}{\tau_{e,i}}}S^{(i)}_{+,in}+\sqrt{\frac{1}{\tau_{e,i}}}S^{(i)}_{-,in} \quad (1)$$

where ω_i is the resonant frequency of the ith aperture-resonator, $1/\tau_{0,i}=\omega_i/(2Q_{0,i})$ is the decay rate due to the intrinsic loss in the ith resonator, and $1/\tau_{e,i}=\omega_i/(2Q_{e,i})$ is the decay rate due to the energy escaping into the bus waveguide. $Q_{0,i}$ and $Q_{e,i}$ stand for the cavity quality factors related to intrinsic loss and coupling loss of the ith resonator, respectively. $Q_{t,i}$ is the total quality factor ($1/Q_{t,i}=1/Q_{0,i}+1/Q_{e,i}$), which can be evaluated from the formula $Q_{t,i}=\lambda/\Delta\lambda$, where the wavelength λ and $\Delta\lambda$ are corresponding to the resonance wavelength and full width of half maximum (FWHM). $Q_{0,i}$ is the intrinsic quality factor, which can be obtained from the following equation [36],

$$Q_o=Re(n_{eff})/2\mathrm{Im}(n_{eff}) \quad (2)$$

The effective refractive index n_{eff} can be obtained from the following relation [6],

$$n_{eff}=\frac{k_{MIM}}{k_0}=\sqrt{\varepsilon_d-2\varepsilon_d\sqrt{\varepsilon_d-\varepsilon_m}/(k_0w\varepsilon_m)} \quad (3)$$

where $k_0=2\pi/\lambda$, $\lambda=2\pi c/\omega$. ε_d and ε_m represent the permittivity of the insulator and the metal, respectively.

From energy conservation and the condition that the light is only injected from the left port ($S^{(i)}_{-,in}=0$), we finally get the transfer function of the system,

$$t=\frac{S^{(2)}_{+,out}}{S^{(1)}_{+,in}}=\frac{t_1t_2}{1-r_1r_2e^{j2\phi}} \quad (4)$$

where $t_i=(M+\tau_{e,i})/(M+\tau_{0,i}+\tau_{e,i})$, $r_i=-\tau_{0,i}/(M+\tau_{0,i}+\tau_{e,i})$ and $M=\tau_{0,i}\cdot\tau_{e,i}\,j\,(\omega_i-\omega)$. The phase shift $\varphi=\omega Re(n_{eff})L/c$ with c being the light velocity in vacuum and L being coupling distance between the two ARS. The output transmittance efficiency can be derived as $T=|t|^2$.

3. Effects of coupling distance on PIT in the indirect coupling mode

Fig. 2(a)–(c) show the transmission spectra with different coupling distance $L=780$ nm, 740 nm and 700 nm, respectively. The lengths of the two ARS are set as $d_1=320$ nm and $d_2=300$ nm, respectively. The solid line is calculated by the FDTD method. Based on the FDTD, we numerically extract the related physical parameters and obtained the theoretical results denoted by circle line. For theoretical transmission spectra, $\omega_1=2.39\times10^{15}$ rad/s, $\omega_2=2.24\times10^{15}$ rad/s, $\tau_{0,1}=5.14\times10^{12}$ rad/s, $\tau_{0,2}=5.09\times10^{12}$ rad/s, $\tau_{e,1}=2.0\times10^{13}$ rad/s, $\tau_{e,2}=2.33\times10^{13}$ rad/s, and $Re(n_{eff})=1.37$. It is obvious that the theoretical results are in accordance with FDTD simulations, from which we can conclude that Eq. (4) is a good theoretical description of PIT in our plasmonic structure. The black spot line in Fig. 2(a) shows the transmission spectrum of the plasmonic structure with a single aperture resonator ($d_1=310$ nm). It is apparent that the transmission spectra in Fig. 2(a)–(c) exhibit typical EIT-like shapes, namely, a transparency peak in the center of an original transmission dip. In terms of the physical nature, the EIT-like effect can be ascribed to a special form of the Fano resonance [37–40]. The EIT-like optical response in our proposed system results from destructive interference between the resonance modes of the two ARS, which is similar to the formation mechanisms of PIT in previously reported coupled-resonator structures [7,19,25]. To further investigate the spectral features, the evolution of the transmission spectrum versus the coupling distance L is depicted in Fig. 2(d). It is found that the transparency peak varies periodically versus L. And for a determined L, the transmission spectrum shows well agreement with Fig. 2(a)–(c). Moreover, the transparency peak presents a shift while its center remains nearly immobile. Hence, it can be concluded that the coupling distance L plays an important role in the evolution of PIT induced by indirect coupling.

4. Respective effects of direct and indirect couplings on PIT

Next, we fixed the coupling distance between the two ARS as $L=780$ nm. Fig. 3(a)–(c) show the transmission spectra with different gold gap distance $G=60$ nm, 40 nm and 20 nm, corresponding to resonator lengths $d_1=d_2=370$ nm, 380 nm and 390 nm, respectively. In such a case, the given values of gold gap G result in the excitation of direct coupling and finally lead to the coexistence of direct and indirect couplings. The solid and circles lines are calculated by the FDTD method and CMT, respectively. It is apparent that the circles line, describing indirect coupling mode,