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Plasmonic analog of electromagnetically induced transparency in paralleled waveguide resonator systems

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ABSTRACT

By adding a resonant waveguide, the electromagnetically induced transparency (EIT) was achieved due to the destructive interference between the side-coupled cavity and the resonant waveguide. The proposed structure was analyzed by the coupled-mode theory and demonstrated by the finite element method. The simulation results showed that not only can we achieve multiple modes EIT-like transmission, but also get a single-mode EIT-like transmission by choosing the proper position of the resonant waveguide. The transparency effect induced by coupled resonance may have potential applications for nanoscale optical switching, nanolaser, and slow-light devices in highly integrated optical circuits.

Electromagnetically induced transparency (EIT) is a special and counterintuitive phenomenon which occurs in atomic systems due to the quantum destructive interference between the excitation pathways to the atomic upper level [1,2]. Recently, tremendous attention has been attracted to the studies that EIT-like optical responses can be obtained in classical resonator systems [3], which are easily realized and integrated into the chips. The EIT-like spectral response was also found in many devices, such as the coupled whispering-gallery microresonators [4], grating [5], coupled photonic crystal cavities [6,7], asymmetric T-shape single slit [8], and coupled-resonator systems [9–11]. As we know, surface plasmon polaritons (SPPs), which are waves that propagate along the surface of a conductor due to the interaction between free electrons in the metal and the electromagnetic field in the dielectric, can overcome the diffraction limit and confine light in sub-wavelength dimensions [12]. A large number of devices based on SPPs, such as bends [13], all-optical control [14], sensors [15], modulators [16], have been investigated numerically and demonstrated experimentally. As an important plasmonic waveguide, the metal–insulator–metal (MIM) structure has attracted more and more attention due to their deep-subwavelength confinement of light [17]. The MIM waveguide has wide applications in deep-subwavelength optical devices, such as filter [18,19], the nanofocusing structure [20], Y-bend combiner [21], plasmonic electro-optical switching [22] and demultiplexers [23–26]. Thus, combining the EIT effect with nanoplasmonic structures would open the possibility to achieve ultra-small sensors and modulators with high sensitivities to variations of the surroundings.

In this letter, a compact optical system, which consists of a side-coupled cavity couples with a MIM waveguide and a resonant waveguide, is proposed and investigated. The theoretical analysis shows that an obvious EIT-like transmission spectrum is observable in our plasmonic structure and demonstrated by the finite element method. Simulation results show that our structure not only can achieve single mode EIT-like transmission, but also can achieve multi-mode EIT-like transmission by choosing the proper position of the resonant waveguide. The relationship between the EIT-like transmission peak wavelengths and the length of the resonant waveguide is given. The corresponding mechanisms for the proposal are discussed followed by qualitative explanations in terms of field distributions.

The investigated waveguide system consists of a MIM waveguides, a side-coupled cavity and a resonant waveguide as shown in Fig. 1. The main parameters of the structure are the length and width of the side-coupled cavity (L_1 and W) and resonant waveguide (L_2 and W), width of bus waveguide (W) and the coupling distance (d_1 and d_2). This system is a two-dimensional model, and the materials in the blue and white areas are chosen to be silver (ε_m), and air ($\varepsilon_d = 1.0$), respectively. The transmission properties of the waveguide system were numerically investigated using the finite element method (FEM) with COMSOL Multiphysics. Since the width of the bus waveguide is much smaller than the wavelength of the incident light, only a single propagation mode TM_0 can exist in the structure. The transmittance of SPPs, T, is defined as the

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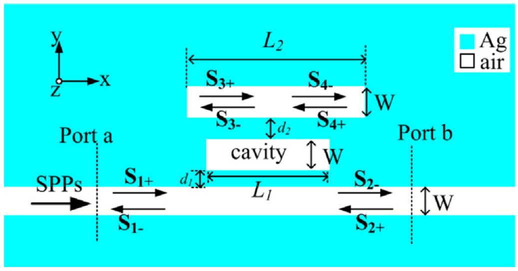

Fig. 1. Schematic of the optical system consisting of a MIM waveguide with a side coupled cavity, a resonant waveguide and the geometrical parameter symbols. The value of $W = 50$ nm is fixed.

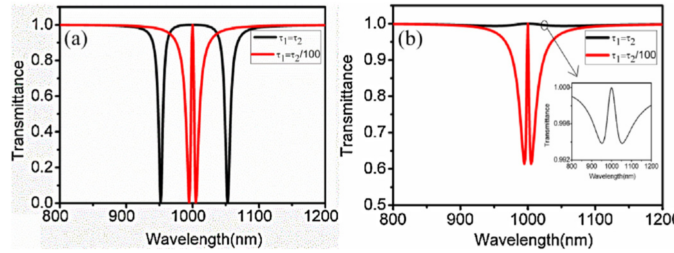

Fig. 2. Theoretical transmission spectra though the optical system as shown in Fig. 1. The spectra are calculated from Eq. (6) with the phase shift $\varphi = 2\pi L_2/\lambda_{SPP}$. (a) $\theta_3 - \theta_4 = 0$; (b) $\theta_3 - \theta_4 = \pm\pi$. The resonant frequency of the cavity is $\omega_0 = 2\pi c/\lambda_0$. The decay rates are taken to be $\tau_1 = \tau_2$ (the black line) and $\tau_1 = \tau_2/100$ (the red line) with $1/\tau_1 = (2\pi c/L_2)/500$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

quotient between the SPPs power flows of port b (P_b) and port a (P_a), which is expressed as $T = P_b/P_a$. The power flows at the ports were obtained by integrating the Poynting vector over the channel cross section. The transmission spectra of the optical waveguide system were obtained by changing the input wavelength λ. Here, the permittivity of Ag can be determined using the Drude model: $\varepsilon_m = \varepsilon_\infty - \omega_p^2/(\omega^2 + i\omega\gamma)$ with $\varepsilon_\infty = 3.7$, $\omega_p = 9.1$ eV, $\gamma = 0.018$ eV [27], which fit the experimental optical constant of silver [28] for the range of 600–2000 nm quite well.

In order to obtain a qualitative understanding of the optical waveguide, we analyze the transmission properties of the optical waveguide system by the temporal coupled mode theory [29]. The optical energy is coupled between bus waveguide and the resonant waveguide through the side-coupled cavity. The amplitude of the cavity is denoted by a and is normalized to the energy in the modes. The amplitudes of the incoming and outgoing waves into the cavity denoted by S_{i+} and S_{i-} ($i = 1$–4) (as shown in Fig. 1) and are also normalized to the power carried by the waveguide mode. The time evolution of the amplitudes of the cavity in steady state can be described as

$$\frac{da}{dt} = j\omega_0 a - \left(\frac{2}{\tau_1} + \frac{2}{\tau_2}\right) a + \sqrt{\frac{2}{\tau_1}} S_{1+} e^{j\theta_1} + \sqrt{\frac{2}{\tau_1}} S_{2+} e^{j\theta_2} + \sqrt{\frac{2}{\tau_2}} S_{3+} e^{j\theta_3} + \sqrt{\frac{2}{\tau_2}} S_{4+} e^{j\theta_4} \quad (1)$$

where ω_0 is the resonant frequency of cavity, $1/\tau_1$ and $1/\tau_2$ defined as the decay rates of the cavity amplitude a into the bus waveguide and into the resonant waveguide, θ_i are the respective phases. By power conservation, the outgoing waves are

$$S_{1-} = S_{2+} - \sqrt{\frac{2}{\tau_1}} e^{-j\theta_2} a \quad (2)$$

$$S_{2-} = S_{1+} - \sqrt{\frac{2}{\tau_1}} e^{-j\theta_1} a \quad (3)$$

$$S_{3-} = S_{4+} - \sqrt{\frac{2}{\tau_2}} e^{-j\theta_3} a \quad (4)$$

$$S_{4-} = S_{3+} - \sqrt{\frac{2}{\tau_2}} e^{-j\theta_4} a \quad (5)$$

The waves in the resonant waveguide should satisfy a steady-state relation: $S_{3+} = S_{3-} e^{-j2\varphi}$ and $S_{4+} = S_{4-} e^{-j2\varphi}$. Here, $\varphi = 2\pi L_2/\lambda_{SPP}$ is the phase shift of the SPPs mode during a round trip of the resonant waveguide. We choose port a as the input port and we get S_{2+} zero. If S_{1+} has a $e^{j\omega t}$ time dependence, then from Eqs. (1)–(5), we get the transmittance T of port b of the system expressed as:

$$T = \left|\frac{S_{2-}}{S_{1+}}\right|^2 = \frac{(((\omega - \omega_0)\tau_1/2) - (\tau_1/\tau_2)\cos(\theta_3 - \theta_4)\cot(2\varphi))^2 + ((\tau_1/\tau_2)(1 - \cos(\theta_3 - \theta_4)))^2}{(((\omega - \omega_0)\tau_1/2) - (\tau_1/\tau_2)\cos(\theta_3 - \theta_4)\cot(2\varphi))^2 + ((\tau_1/\tau_2)(1 - \cos(\theta_3 - \theta_4)))^2 + 1} \quad (6)$$

It should be mentioned that the electromagnetic wave coupled into the resonant waveguide exhibits Fabry–Perot oscillations and forms standing-wave modes when the phase-matching condition

$$\varphi(\omega_m) = m\pi \quad (7)$$

is satisfied ($m = 1$, 2 and ω_m is the resonant frequency of the standing-wave modes).

To analyze the dependence of the transmission on the decay rates into the bus waveguide and the resonant waveguide, we plot the intensity transmission spectra in Fig. 2(a) and (b) that are calculated from Eq. (6) when $\theta_3 - \theta_4 = 0$ and $\theta_3 - \theta_4 = \pm\pi$, respectively. From Fig. 2, we find that the shapes of the spectrum features depend on $1/\tau_2$. Small $1/\tau_2$ leads to a narrow resonant transmission peak between the two transmission dips. If we adjust the parameters of the optical system with sufficient range, the transmittance of the proposed structure will change from minimum to maximum, which is the main reason of the EIT-like transmission. The analysis results are demonstrated by the simulation results.

Based on the theoretical analysis, the FEM is used to investigate the transmission characteristics of the proposed structure. From Fig. 1, we know that the side-coupled cavity coupled strongly to the bus waveguide, so called the bright mode. However, the resonant waveguide cannot directly couple to the bus waveguide, supporting the dark mode. If d_2 exceed the skin depth of SPPs in the metal, the dark mode cannot be excited. In this case, the structure shown in Fig. 1 can be a simple side-coupled bandstop filter structure shown in Fig. 3(a). Fig. 3(b) shows the transmission spectrum when $L_1 = 500$ nm and $d_1 = 35$ nm. Two resonant dips are obtained at 1500 nm and 768 nm, which are corresponding to the first and second resonant mode, respectively. The distributions of |Hz| at the two resonant dips are shown in Fig. 3(c) and (d), respectively.

Then, if d_2 is within the skin depth of SPPs in the metal, the dark mode will be excited through tunneling coupling with the bright mode due to the greatly enhanced near-field interferences between them and the case will be different. As shown in Fig. 4(a), the black dotted line is in the middle of the side-coupled cavity, here, $L_1 = 500$ nm, $L_2 = 500$ nm, $d_1 = 35$ nm and $d_2 = 35$ nm. Fig. 4(b) shows the transmission spectrum of the proposed optical system. From it we can see that EIT-like transmission appears at the original dips. The new emerging peaks are at 1487 nm and 761 nm, and the corresponding field distributions of |Hz| are shown in Fig. 4(c) and (d), respectively. From Figs. 3(c), (d) and 4(c), (d), we can see