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Analogy of electromagnetically induced transparency in plasmonic nanodisk with a square ring resonator

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ABSTRACT

We have demonstrated the analogy of electromagnetically induced transparency in plasmonic nanodisk with a square ring resonator. A reasonable analysis of the transmission feature based on the temporal coupled-mode theory is given and shows good agreement with the Finit-Difference Time-Domain simulation. The transparency window can be easily tuned by changing the geometrical parameters and the insulator filled in the resonator. The transmission of the resonator system is close to 80% and the full width at half maximum is less than 46 nm. The sensitivity of the structure is about 812 nm/RIU. These characteristics make the new system with potential to apply for optical storage, ultrafast plasmonic switch and slow-light devices.

1. Introduction

Electromagnetically induced transparency (EIT) as a thrilling and counterintuitive phenomenon shows a narrow spectral transparency region in a broad absorption regime, which occurs in three energy level atomic systems due to the quantum destructive interference between the excitation path-ways to the atomic upper level [1,2]. This phenomenon has received much attention due to its interesting physics [3,4] and potential applications such as the transfer of quantum correlations [5], slow light propagation [6], and so on. However, the demands of stable gas lasers and low temperature environment severely hamper the implementation of EIT in chip-scale application. Recently, EIT-like has been observed in many systems such as photonic crystal nanocavity [7], hybrid plasmonic waveguides [8,9], symmetric planar metamaterial [10], and resonator [11–13]. Among these systems, the EIT-like effect based on the surface plasmon polaritons (SPPs) has been favored more and more by researchers.

Surface plasmon polaritons are a kind of electromagnetic waves propagating along the metal–dielectric interface with an exponential decaying field on both sides [14]. Due to the capabilities of overcoming the classical diffraction limit and manipulating light in the nanoscale domain, SPPs have been considered as one of the most promising energy and information carriers [15,16]. So far, numerous EIT-like devices based on SPPs such as Fabry–Perot resonator [17], Fano resonances [18,19], asymmetric dual side-coupled cavities [20], stub waveguide with ring resonator [21] have been investigated theoretically and demonstrated experimentally. Among multitudinous plasmonic structures, the plasmonic analogous to EIT in the metal–insulator–metal (MIM) waveguide systems [22–24] draw much attention because of the deep-sub-wavelength confinement of light and relatively simple fabrication [25]. An intriguing potential application for such plasmonic analogue of EIT structures is their use in light manipulation and transmission in nanoscale devices.

In this paper, a new kind of analogies of EIT in metal–insulator–metal plasmonic waveguide consisting of a square ring resonator coupled with a nanodisk is proposed and numerically investigated. We firstly briefly reviewed the properties of basic geometry, then theoretically analyzed this structure by the temporal coupled-model theory (CMT). Especially, in order to understand the relationship between the transmission characteristics and geometrical parameters of the structure and refractive index of insulator, we acquired the intuitive images by Finit-Difference Time-Domain (FDTD) simulation. The results show that the transparency window can be easily tuned by changing the geometrical parameters of the structure and the EIT-like resonant peak has a linear relationship with refractive index. These results may inspire interest in nanoscale wavelength-filter, slow light devices and optical switching elements in highly integrated optical circuit.

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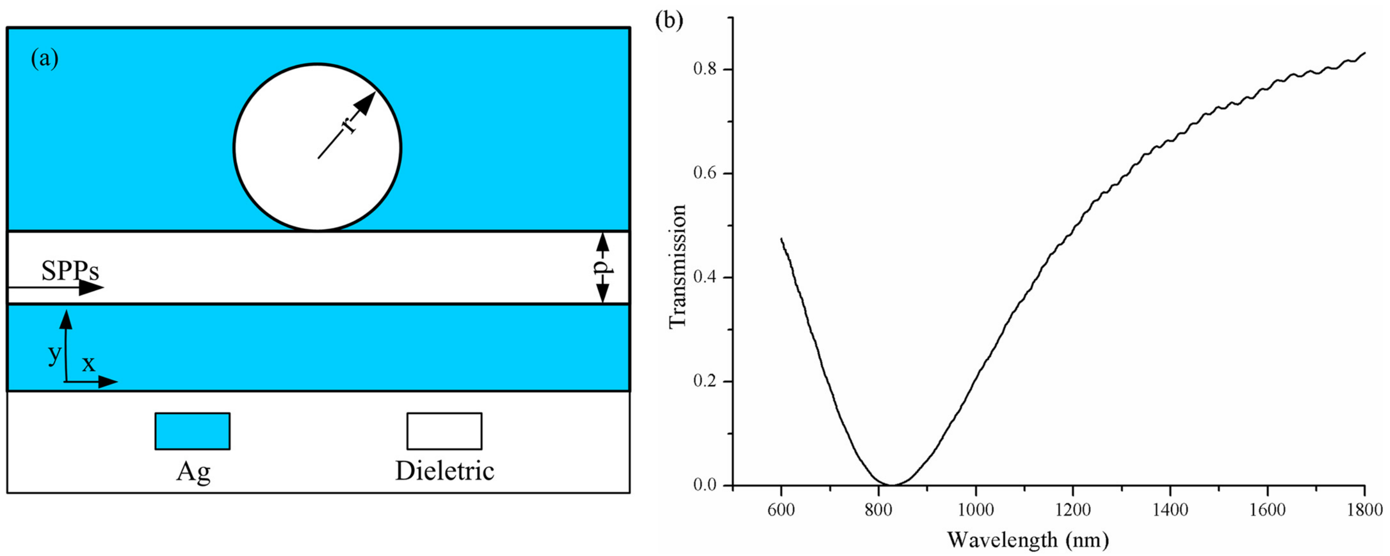

Fig. 1. (a) Schematic of MIM waveguide directly coupled to a nanodisk resonator with gap = 0. (b) Transmission spectra for MIM waveguide directly coupled to nanodisk, with d = 50 nm and $r = 57$ nm.

2. Theoretical analysis and discussion of MIM waveguide with one nanodisk resonator

To start, let us firstly briefly review the properties of basic geometry as shown in Fig. 1(a), the nanoscale plasmonic resonator system with one nanodisk directly coupled to a bus waveguide. The dielectric layer here is assumed to be air ($n = 1$) and the background material in blue is silver. The permittivity of the metallic region can be described by the Drude mode [26]:

$$\varepsilon_{\mathrm{m}}(\omega) = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \qquad (1)$$

where $\varepsilon_{\infty} = 3.7$ is the dielectric constant at infinite frequency, $\omega_p = 9.1$ eV is the bulk plasma frequency of free conduction electrons, $\gamma = 0.018$ eV is the electron collision frequency and ω is the angular frequency of incident light in vacuum.

Fig. 1(b) shows the transmission spectra for the MIM waveguide directly with one nanodisk resonator. According to CMT [27,28], the transmission of the system supporting a resonant mode can be indicated as:

$$T = \frac{(\omega - \omega_0)^2 + (1/\tau_0)}{(\omega - \omega_0)^2 + (1/\tau_0 + 1/\tau_e)} \qquad (2)$$

where τ_0 and τ_e are the decay rate due to the intrinsic loss and waveguide coupling loss, respectively. It is obvious that the minimum transmission $T_{\min} = \frac{(1/\tau_0)^2}{(1/\tau_0 + 1/\tau_e)^2}$, when $\omega = \omega_0$. As the size of the structure is much smaller than incident wavelength, the intrinsic loss can be neglected, then $T_{\min} = 0$, which is accordance well with the numerical simulation.

3. EIT-like in a square ring resonator coupled with a nanodisk

The schematic illustration of EIT-like in metal–insulator–metal plasmonic system we proposed is shown in Fig. 2(a), it is composed of a nanodisk coupled with a square ring resonator. The inner and outer length of the square ring are $l_1 = 75$ nm and $l_2 = 240$ nm, respectively. More, in order to explain the subsequent analysis clearly, we set center length of square ring $l = (l_1 + l_2)/2$. The width of bus waveguide is set to be d = 50 nm. The radii of nanodisk is $r = 57$ nm and the distance between the nanodisk and square ring is $g = 11$ nm. Fig. 2(b) shows the transmission spectra without and with the square ring resonator. Without the square ring resonator, the transmission spectrum exhibits a spectral dip at the resonance wavelength of 825 nm due to the destructive interference between the incident wave and escaped power from the resonator [29]. However as the nanodisk and square ring are combined into a composite structure as shown in Fig. 2(a), the transmission spectrum exhibits a narrow transparency peak in the transmission dip near the resonant wavelength of the ring resonator, the EIT-like transparency peak is close to 80% and the full width at half maximum (FWHM) is less than 46 nm.

In order to have an insight into the physical mechanism behind the EIT-like effect in the new proposed system, we plot the electric field. Figs. 2(c) and (d) show the field distributions at the EIT-like transparency peak of 825 m without and with the square ring resonator. As shown in Fig. 2(c), the incident lights are reflected in the nanodisk-shaped waveguide, so that the whole modes are locked in the nanodisk, whereas they pass through the waveguide with ring resonator, as can be seen in Fig. 2(d). The results are consistent with the spectral response in Fig. 2(b). It is worth noting that the electromagnetic field in the nanodisk is weakened due to the interference effect when the disk couples with the square ring cavity.

In order to analyze the EIT-like phenomenon in detail, we introduce a CMT-based transmission line theory. As shown in Fig. 2(a), the coupling coefficient between the bus waveguide and the nanodisk is denoted by γ, β is the coupling coefficient between the nanodisk and the square ring. α, δ are the decay rates due to the internal loss of nanodisk and square ring, respectively. The amplitudes of the incoming and outing waves of disk are denoted by S_{+11}, S_{+12}, S_{-11}, and S_{-12}, as seen in Fig. 2(a). The temporal evolution of the amplitude A of the single nanodisk and B of the square ring. The characteristic equation can be given:

$$\frac{\mathrm{dA}}{dt} = (j\omega_t - \alpha - \beta - \gamma)A + j\sqrt{\gamma}(S_{+11} + S_{+12}) + j\sqrt{\beta}B \qquad (3)$$

$$\frac{\mathrm{dB}}{dt} = (j\omega_n - \beta - \delta)B + j\sqrt{\beta}A \qquad (4)$$

where ω_t, ω_n are the resonant frequency of the nanodisk and square ring, respectively. Due to energy conservation and the time reversal symmetry, the relationship of the incoming and outing waves in the bus waveguide can be denoted as:

$$S_{-11} = S_{+12} + j\sqrt{\gamma}A \qquad (5)$$