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Dual coupled-resonator system for plasmon-induced transparency and slow light effect

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ABSTRACT

We proposed a dual coupled-resonator system based on the metal-insulator-metal bus waveguide and numerically investigated the plasmon-induced transparency and slow light effect with the Finite-Difference Time-Domain simulations in this paper. The electromagnetically induced transparency-like spectral response will occur between two adjacent stub resonators with detuned resonant wavelength due to the phase-coupled effect. The transmissivity and group index equations were been deduced, which indicated that the system can achieve the effect of the multiple electromagnetically induced transparency-like and slow light. With the optimization, the single peak transmission can reach to as high as 92%, dual PIT transmission peaks appear, as well as group index can reach over 75. These characteristics indicate multiple applications of our system in integrated optical circuits.

1. Introduction

Electromagnetically induced transparency (EIT) is a wizardly phenomenon which was observed primarily in an atomic system when Boller et al. applied a coupling laser on Sr vapor [1]. It had been investigated [2] that the distinct feature of EIT is due to the quantum destructive interference between two different excitation pathways to upper state. After EIT-effect had been pointed out, dramatic group velocity reduction resulting from the extraordinarily strong dispersion around the transparency window shows promising applications in a wide range of optical science, e.g. nonlinear optical processes, ultrafast switching, optical data storage [3,4]. However, requirement of rigorous conditions e.g. macroscopic apparatus, stable gas lasers, and low temperature environments [3] to observe the EIT-effect make it extremely difficult to realize the on-chip applications with traditional EIT. Fortunately, several practical solutions-under which the implements could realize in a relatively easy way and achieve the desired EIT spectral response simultaneously-had been proposed and demonstrated, such as metamaterial-induced transparency [5–7], coupled-resonator-induced transparency [8,9] and plasmon-induced transparency (PIT) [10–12]. Within the schemes above, the PIT has become a mushrooming field of research in recent years due to their suitable for chip-scale implementation, thanks to the capability to overcome the diffraction limit of light by deliver information with surface plasmon polaritons (SPPs) [13]. In addition, the metal-insulator-metal (MIM) structure provides feasible way to observe the EIT effect due to its strong light confinement.

Previous researchers summarized [14,15] two ways to generate the EIT-like spectral response in waveguide-resonator system: the near-field coupling between modes of a radiative resonator (directly coupled to main waveguide) and a subradiant resonator (not coupled to waveguide) [16]; phase coupling by means of two detuned resonator coupled to a bus waveguide [17–19]. Each scheme above has its own feature in performing EIT-like effect and draw a great many focus in nanoscale device field. It can't help driving us to unite this two schemes into a more powerful one.

In this work, we propose a dual coupled stub-nanodisk plasmonic system based on MIM bus waveguide to realize the EIT-like spectral response. Under the two dimension Finite-Difference Time-Domain (2D-FDTD) method [20] with a perfect matched layer (PML) boundary condition, we have optimized this scheme to reach relatively high transmittance and narrow full width at half-maximum (FWHM) in contrast to most of the previous PIT system, for instance Ref [11]. Also, theoretical analysis with couple mode theory (CMT) [21,22] reveal that our work have a high-performance in slow light effect as a result of the high coupling coefficient and quality factor.

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2. Structure model and simulation

Fig. 1 describes the geometry of the proposed dual coupled-resonator system which consists of two stub resonators and two nanodisk resonators on the opposite sides of the MIM bus waveguide. Silver (the blue color area) and air (the white color area, $\varepsilon_\alpha = 1$) are selected as the metal material to excite SPPs wave and the insulator inside the silver, respectively. The two stubs have the same length l and width w. The radii of two nanodisks are R_1 and R_2, respectively. L is the distance between the two cavities and g is the gap between the nanodisk and the stub. We suppose that the width of the bus waveguide d is equal to 50 nm and invariable in this letter.

The frequency dependent dispersive permittivity of Ag is described by the well-known Drude model [22], which is well fitting with the experimental optical constant in Ref [23], as

$$\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma_0)} \tag{1}$$

where $\varepsilon_\infty = 3.7$ represents the dielectric constant at infinite angular frequency, $\gamma_0 = 0.018$ eV is the electron collision frequency, $\omega_p = 9.1$ eV stands for the bulk plasma frequency and ω is the angular frequency of incident light. Spectral responses and average field distributions characteristics of the proposed system are obtained by 2D-FDTD simulation with spatial steps of $\Delta x = \Delta z = 3$ nm and temporal step of $\Delta t = \Delta x/(2c)$ (c is the velocity of light in vacuum), respectively. Planar impulse is applied as the excitation in this simulation.

3. Theoretical analysis

A simplified theoretical model in CMT-based transmission line theory [4,24] is deduced as follow in order to analysis the EIT-like spectral response. As shown in Fig. 1, $S^i_{p,in}$ and $S^i_{p,out}$ ($i = 1, 2$) represent the energy amplitudes of the incoming and outgoing waves in the bus waveguide while the subscript $p = +/-$ stands for the input/output direction of waveguide modes, respectively. In order to study symmetrical case, we suppose that the loss of nanodisk, the loss of stub, the coupling coefficient between the waveguide and stub, the coupling coefficient between stub and nanodisk are all the same as the other one. By ignoring the light propagation, the time evolution of stub's/nanodisk's mode amplitude in steady state can be described as (2)/(3)

$$\frac{dA_i}{dt} = (j\omega_0 - \alpha_s - \beta)A_i + \sqrt{\beta}\,(S^i_{+,in} + S^i_{-,in}) - j\gamma B_i \tag{2}$$

$$\frac{dB_i}{dt} = (j\omega_0 - \alpha_n)B_i - j\gamma A_i \tag{3}$$

where ω_0 represent the resonance frequency of the stub/nanodisk, $\alpha_s = \omega_0/(2Q_s)$, $\alpha_n = \omega_0/(2Q_n)$, $\beta = \omega_0/(2Q_w)$ and $\gamma = \omega_0/(2Q_c)$are the decay rate of stub, the decay rate of nanodisk, the coupling coefficient between the bus waveguide and stub and the coupling coefficient between stub and nanodisk, respectively. Q_s, Q_n, Q_w and Q_c stand for the intrinsic quality factor [12] of stub, the intrinsic quality factor of nanodisk, the coupling quality factor between the bus waveguide and stub and the coupling quality factor between stub and nanodisk, respectively. j is the imaginary unit. By applying the power conservation, the outgoing waves of the i-th cavity can be shown as:

$$S^i_{-,out} = S^i_{-,in} + j\sqrt{\beta}A_i \tag{4a}$$

$$S^i_{+,out} = S^i_{+,in} + j\sqrt{\beta}A_i \tag{4b}$$

Ignoring the nonlinear effect, the field around the system

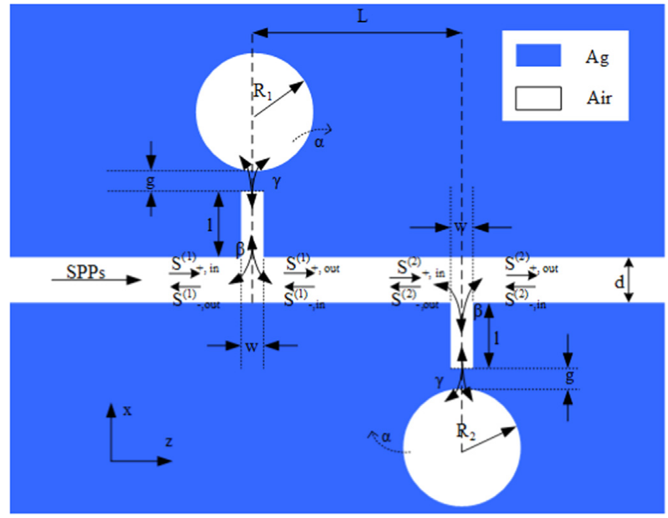

Fig. 1. Schematic diagram of proposed nanoscale plasmons system.

oscillates as $e^{j\omega t}$, so that

$$dA_i/dt = j\omega A_i \tag{5a}$$

$$dB_i/dt = j\omega B_i \tag{5b}$$

Using Eqs. (2)–(5), the transmission and reflection coefficients are derived as

$$t_i(\omega) = 1 - \frac{\beta}{\varepsilon} \tag{6a}$$

$$r_i(\omega) = \frac{\beta}{\varepsilon} \tag{6b}$$

Here, let

$$\varepsilon = j(\omega - \omega_0) + \alpha_s + \beta - \frac{\gamma^2}{j(\omega - \omega_0) + \alpha_n} \tag{7}$$

As the cavity–cavity phase difference is approximately equal to 0, it can be neglected and the model can be simplified model to the Fabry-Perot resonator, which the transmission efficiency can be deduced to

$$T = \left|\frac{S^2_{+,out}}{S^1_{+,in}}\right|^2 = \left|\frac{t^2}{1 - r^2}\right|^2 \tag{8}$$

Combining Eqs. (6a), (6b) and (8), the expression of transmission simplify to

$$T = \left|\frac{\varepsilon - \beta}{\varepsilon + \beta}\right|^2 \tag{9}$$

The complete form of transmission can be transform to

$$T = \left|1 - \frac{2\beta}{j(\omega - \omega_0) + \alpha_s + 2\beta - \frac{\gamma^2}{j(\omega - \omega_0) + \alpha_n}}\right|^2 \tag{10}$$

From the Eq. (10), we can predict that an EIT-like peak will appear when the cavity is tuned into a suitable resonant frequency ($\omega = \omega_0$).

4. Simulation results and discussion

To investigate the variation of the transmittance correspond to different parameters with the structure so as to obtain an optimal