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Plasmonic-induced transparency based on plasmonic asymmetric dual side-coupled cavities

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ABSTRACT

A method of the analog of electromagnetically induced transparency (EIT) in plasmonic metal–dielectric–metal (MIM) waveguide is proposed by using two asymmetric side-coupled cavities and simulated by Finite-difference time-domain (FDTD). The simulation results show that the transparency peak of EIT is very sensitive to the width difference of two cavities and the difference of coupling distances of two cavities with the bus. Furthermore, we find that high transmission of EIT-peak usually accompanies a relatively low quality factor. These properties of our novel plasmonic structure would pave the way for highly integrated optical circuits and optical information processing.

1. Introduction

Surface plasmon polaritons (SPPs) are the type of transverse electromagnetic waves that propagate alone in interface of metal–dielectric–metal (MIM) and forme evanescently fields to the interface. Owing to the capabilities of overcoming the traditional optical diffraction limit and manipulating optical wave in the nanoscale field, SPPs have the more preponderance to realize the highly integrated optical circuits [1–4]. Till now, the MIM SPPs have been applied in many aspects, for instance, sensors [5,6], bend waveguide device [7], wavelength demultiplexers [8–10], filters [11–14], all-optical switches [15–18], optical amplifiers [19], Mach–Zehnder interferometers [20], nanowires [21], polarization analyzers [22], and beam manipulators [23,24]. They are all researched in experiment and theory in recent years.

Electromagnetically induced transparency (EIT) is a quantum phenomenon produced in a three state atomic systems caused by the destructive quantum interference between two probable excitation pathways to atomic levels. It is a typical optical nonlinearity which presents a medium transparency between a small spectral range in broader absorption band, i.e. a spectral “window” of transparency [25,26]. Nevertheless, researches on EIT are severely limited by the demanding conditions: two of the three states should be “dipole allowed” and the last state should be “dipole forbidden”. Due to the inherent coherence of photons which are emitted by a laser, many effects are hardly attainable in atomic, but can be easily visualized and justified in optic system. Recently using micro-coupled resonator to achieve the EIT effect has been reported [27], thus classical quantum phenomena was brought into the domain of optics. Plasmonic induced transparency (PIT) is an EIT-like effect simulated in the plasmonic systems because of its slow-light factor and optical properties. Zhang et al. [28] attained the PIT phenomenon in a unique plasmonic structure at first. They proposed a newfangled molecule that closely resembles the PIT phenomenon of atomic systems. Thereafter, Liu et al. [29] verified PIT using stacked optical metamaterial experimentally. Recently, PIT can be achievable in various kinds of systems such as arrayed metallic nanoparticles [30], electric optical dipole antennas [31], and plasmonic waveguide systems [32].

In this paper, we propose an asymmetric dual side-coupled cavities structure to realize the PIT phenomenon. We choose the width of cavity and the coupling distance as variations to achieve the desired effect. Comparing with previous PIT-like structures, our structure is more compact and easily made up. In this new structure, the destructive interference of the 2nd-order resonance mode of the two cavities can be used to produce the PIT-like phenomenon. By using the 2D-FDTD method, from a series of transmission spectrums with different cavity width and coupling distance, we obtain a conclusion that high transmission always comes with a correspondingly low quality factor which is of great importance for further PIT investigation.

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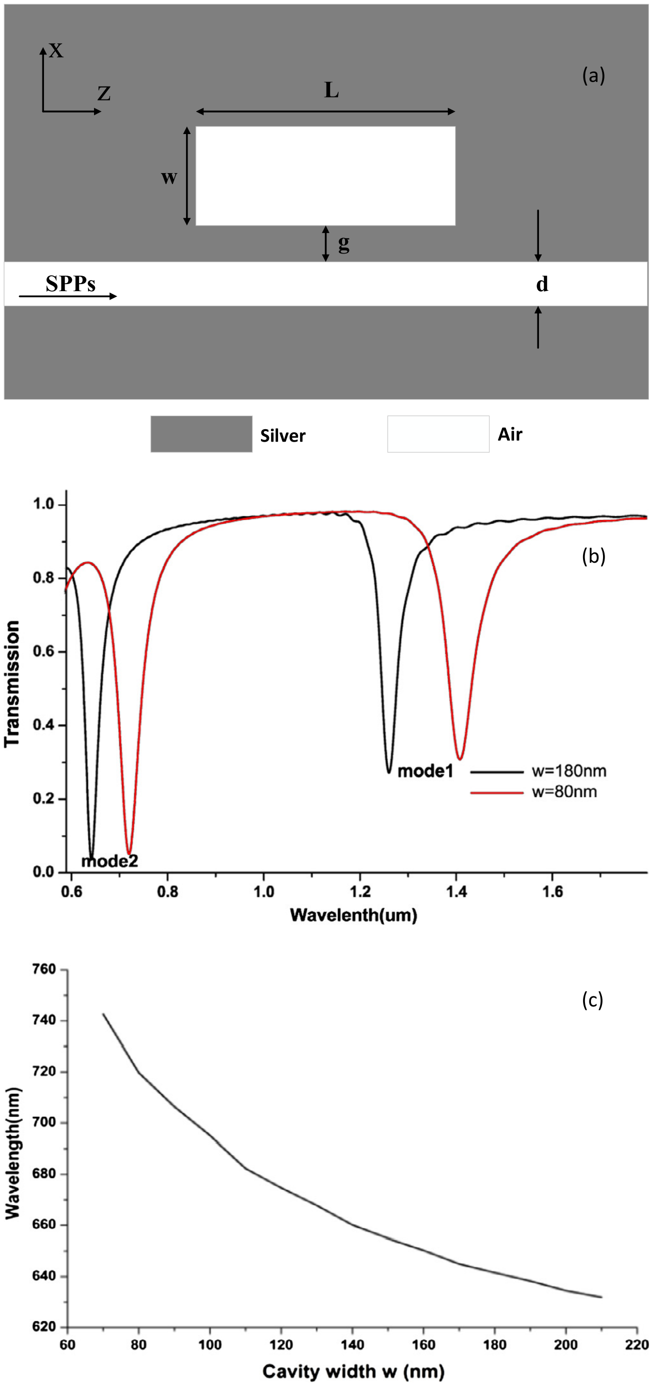

Fig. 1. (a) Schematic diagram of the single side-coupled cavity structure with cavity length $L = 512$ nm, width $w = 80$ nm, gap width $g = 28$ nm, and waveguide width $d = 50$ nm. (b) The transmission spectrum of the single side-coupled cavity structure with width $w = 80/180$ nm. (c) Relationship between the peak resonance wavelengths and the cavity width w.

2. Single side-coupled cavity in MIM waveguide

In Fig. 1(a), we present the single side-coupled resonator plasmonic structure. In this structure, the cavity length L is set 512 nm. The width of cavity w is 80 nm and the distance between the waveguide and the cavity g is 28 nm. The width of waveguide d is 50 nm, which is smaller than the wavelength of the guide. Thus we only need to consider the fundamental mode of waveguide. We assume that the medium of the cavity and waveguide is air and its refractive index is 1 ($n = 1$). The gray background metal is Ag, and its dispersive permittivity could be characterized by the famous Drude model:

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

Here $\varepsilon_\infty = 3.7$ is the relative dielectric constant at the infinite-frequency. $\gamma = 2.73 \times 10^{13}$ Hz is the electron collision frequencies. $\omega_p = 1.38 \times 10^{16}$ Hz is the large plasma frequency and it represents the natural frequency of the conduction electron with oscillating. ω is the angular frequency of incident light.

When the incident light transmits through the bus, some of the energy would be coupled into cavity segment. Thus, part of the energy would be would be transmitted, and part of the energy would be reflected. The resonant condition could be attained by the coupled-mode theory (CMT) [33]. The transmission T closed to the resonant frequency of system is described as

$$T = \frac{(\omega - \omega_0)^2 + (1/\tau_i)^2}{(\omega - \omega_0)^2 + (1/\tau_i + 1/\tau_w)^2}. \tag{2}$$

Here, ω is the angular frequency of incident light, and ω_0 is the resonant frequency of system. $1/\tau_i$ stands for the decay rate of the internal loss in the cavity, and $1/\tau_w$ stands for the energy that escapes through the waveguide. Therewith, we can conclude that while the frequency of incident light is equal to resonance frequency, we will obtain the minimum transmission ratio $T_{\min}$, and the transmittance of resonance peak transmittance $T_{\min} = (1/\tau_i)^2/(1/\tau_i + 1/\tau_w)^2$ would be close to 0 if $1/\tau_w$ is far more than $1/\tau_i$.

In Fig. 1(b), we show the model can serve as a band-stop filter. In order to realize the PIT phenomenon in next section, we change the structure parameter w, which is the width of the cavity, to operate the resonant wavelength with FDTD simulations [34]. As shown in Fig. 1(c), we notice that λ versus w is a nonlinear decrease. In the two-dimensional FDTD simulations, the grid sizes in the x and z directions are selected as 3×3 nm, which is enough to keep convergence.

3. PIT-like feature in dual side-coupled cavities

For the MIM waveguide with two side-coupled cavities when $w_1 \neq w_2$, the PIT window could be produced by the destructive interference of the two cavities. Fig. 2(a) depicts the structure of the dual cavities side-coupled with MIM plasmonic waveguide. The upper cavity has wide $w_1 = 80$ nm and horizontal length $L = 512$ nm, while the lower cavity has wide $w_2 = 180$ nm and the same length L. The bus waveguide is embedded between the two cavities with a gap distance $g_1 = g_2 = 28$ nm for them respectively.

In Fig. 2(b), the two detuned cavities cause two resonance dips at 637 nm and 718 nm and they are the 2nd-order resonance modes of each cavity. It is distinct that there is a PIT-like transmission pick at 679 nm with 0.7 transmission, which is caused by the offset of the opposite functions of two detuned cavities. Here, we regard our system as a Fabry–Perot resonator featured with two frequency-dependent reflectors [35]. And because the separation of two cavities is zero, the transmission of our system can be expressed as [36]

$$T_{PIT}(\lambda) = \left| \frac{t_1(\lambda) t_2(\lambda)}{1 - r_1(\lambda) r_2(\lambda)} \right|^2, \tag{3}$$

where $t_{1,2}(\lambda)$ and $r_{1,2}(\lambda)$ are the frequency-dependent transmission and reflection coefficients in each detuned plasmonic Fabry–Perot resonator.

In order to optimize our result, we choose different geometrical parameters to achieve PIT behavior. For simplicity, we set