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Plasmonically induced reflection in MIM plasmonic waveguide resonator system

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ABSTRACT

Plasmonically induced reflection (PIR) is numerically achieved based on bright-dark coupling mechanism in plasmonic waveguide resonator system. The system consists of a rectangle cavity side-coupled to a metal-dielectric-mental (MIM) waveguide coupled with a ring. The transmission properties of the system are simulated by the finite-difference time-domain (FDTD) method and theoretically explained by the three-level atomic system theory. The results show that the PIR window can be tuned vertically and horizontally, respectively. In addition, double PIR windows appear in the original broadband absorption window by adding another side-coupled rectangle cavity, and the physical origin is presented. Obviously, our structures have potential application for optical switching, filter and spectral splitter in highly integrated optical circuit.

1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic waves coupled to the propagating free electron oscillations and propagate at metal-insulator interfaces [1–3]. Due to breaking the classical diffraction and controlling light in nanometer scale, SPPs have been considered as the most promising information carriers and energy [4–6]. Large number of devices on the basis of SPPs, for example demultiplexer [7], sensors [8–10], optical switches [11] and filters [12–14], were presented and studied in theory and experiment. Electromagnetically induced transparency (EIT) with quantum effect was observed in atomic system due to interference between two excitation pathways [15,16]. EIT enables strong dispersion and resonance in the transparent window, showing enormous potential in optical data storage and slow light domain [17]. However, keeping electronic coherence strictly limits application on the basis of quantum EIT. Fortunately, the EIT-like effect can be easily realized in plasmonic system. Usually, generating EIT-like behavior has two ways as follow: two bright resonators are coupled to a waveguide [18,19] and a dark resonator is coupled with a bright resonator [20,21]. Plasmonically induced transparency (PIT), the novel phenomenon analogous to EIT, is based on plasmonic resonances [22]. Similar to the EIT-like, the bright-dark coupling mechanism enables plasmonically induced reflection (PIR) effect [23]. Opposite to the EIT-like (a transparency peak obtained in a dip), for the PIR, the sharp transmission dip is achieved in the intrinsic band-pass filtering transmission peak [11]. It should be noted that the plasmonic-induced absorption (PIA) is an enhancement of the absorption resulting from atomic coherence induced by optical radiation [24], could also be achieved with the MIM waveguide systems. Li et al. realized the ultra-narrowband PIR window in an MIM waveguide coupled resonator system, and can also control the number of the

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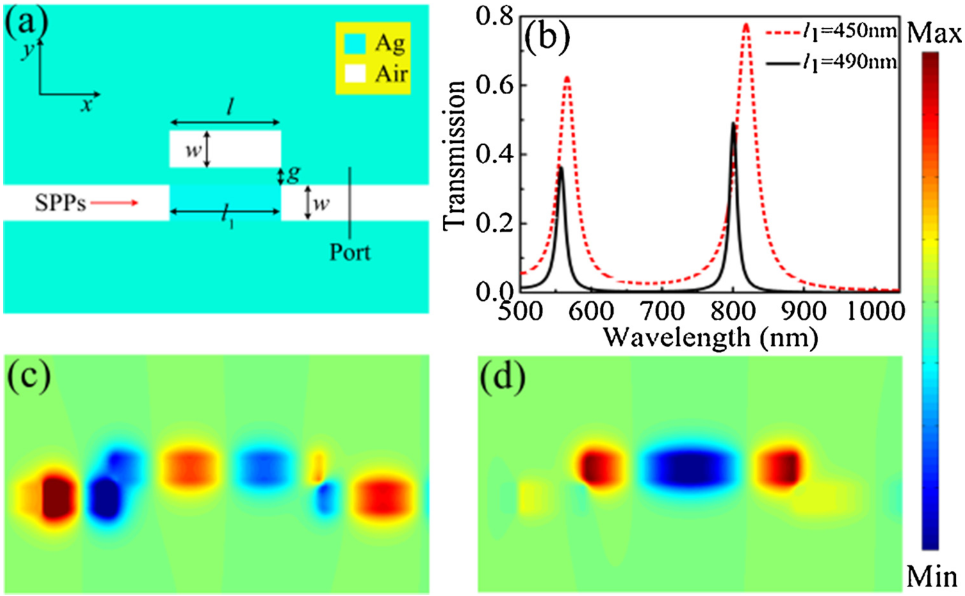

Fig. 1. (a) Schematic diagram with rectangle resonator coupled to the waveguide. (b) Transmission characteristic with l_1 = 450 nm (red curve) and l_1 = 490 nm (black curve). (c)– (d) The H_z distribution respectively corresponding to λ = 557, 800 nm, with l_1 = 490 nm (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

transmission dips [11]. Zhang et al. obtained the PIR window in MIM waveguides with two silver baffles coupled square ring resonator [25]. In addition, it has been reported that the PIR window can also be achieved in the mid-infrared (MIR) region by the graphene-coupled side resonators [26]. Meaningfully, the PIR effect will contribute to optical switch, spectral splitter, filter in integrated circuit and important potential applications in plasmonic sensing [27,28].

Inspired by above basic research, we intend to acquire a PIR phenomenon in MIM waveguide structure with rectangle and ring resonators. The rectangle resonator coupled to the waveguide acts as bright mode and the ring resonator coupled to the rectangle is regarded as dark mode. The results reveal that the PIR behavior is achieved due to bright-dark destructive interference coupling in our designed system. The PIR window can be flexibly tuned vertically and horizontally. Moreover, in order to meet different need, the original absorption window can be separated into two narrowband windows by simple design.

2. Results and discussion

As shown in Fig. 1(a), the rectangle resonator (width w and length l) is coupled to the waveguide with width w. g is the coupling distance between rectangle resonator and waveguide. Different to the common side-coupled structure [28], the MIM waveguide is separated by a metal barrier with length l_1. l_1 is much bigger than skin depth of SPPs, so the left incident SPPs cannot transmit through the metal barrier to right output port. In the structure, the materials in the green and white areas are silver and air, respectively. The relative permittivity of silver is described by the Johnson-Christy model [29]. Since the w is far less than length of incident light, only TM_0 mode can exist in the system, and the dispersion equation of TM_0 mode is: [21]

$$\varepsilon_d\sqrt{\beta_{SPP}^2-\varepsilon_m k_0^2}+\varepsilon_m\sqrt{\beta_{SPP}^2-\varepsilon_d k_0^2}\tanh(w\sqrt{\beta_{SPP}^2-\varepsilon_d k_0^2}/2)=0 \tag{1}$$

The transmission characteristics of the plasmonic system are calculated by the finite-difference time-domain (FDTD) method. In the calculation, the values of w and g are respectively set 50 nm and 10 nm throughout the article.

Fig. 1(b) shows the calculated transmission spectra, red and black curve corresponding to l_1 = 450 nm and l_1 = 490 nm, respectively. The black curve for l_1 = 490 nm is initially discussed. It is clearly see that two peaks emerge at λ = 557 and 800 nm in the transmission spectrum, revealing an outstanding narrowband pass filtering effect. The H_z amplitude distributions at wavelengths λ = 557 and 800 nm are displayed in Fig. 1(c) and (d), respectively. According to Fig. 1(c), the wavelength corresponding to λ = 557 nm is localized in the rectangle cavity and satisfies the fourth-order standing wave resonance. Similarly, the third-order resonance mode is formed at wavelength λ = 800 nm, as shown in Fig. 1(d). Clearly, the SPPs reflect back and forth between two ports of the rectangle, forming a Fabry-Perot (FP) resonator whose resonance condition is described as $2\,\mathrm{Re}(\beta)l+2\Phi=2m\pi$ [30]. Attribute to the resonance, the left incident SPPs are coupled into the right waveguide output port, enabling the transmission peaks at λ = 557 and 800 nm. However, when the length l_1 of the barrier reduces from 490 to 450 nm, the transmission of these two peaks markedly increases and has a slight red shift (see Fig. 1(b)), which is attributed mainly to the increased coupling distance between the waveguide and the rectangle cavity. Note that the length l_1 of the barrier is always 490 nm in the article below.

In comparison with the EIT-like effect on the basis of bright-dark coupling mechanism where transmission peak appears in

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