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Fano resonance and Rabi splitting in MDM side-coupled cavities systems

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ABSTRACT

We theoretically investigate the Fano resonance and Rabi splitting in the metal–dielectric–metal plasmonic waveguides with stub resonators. The proposed nanostructure waveguide consists of bulb-like resonators and a thin Metamaterial (MM) baffle. The bulb-like resonator with low Q factor can work as a continuum state, and the plasmonic waveguide inserted with a MM baffle can work as a discrete state. Fano resonances are obtained because of the interaction between the two states in the structure and the Fano resonance can be tuned by changing the separation between the resonator and the MM baffle. In the plasmonic waveguide system with two resonators and a MM baffle, Rabi splitting occurs because of the strong coupling between the narrow spectral response of MM baffle and the Fabry–Perot resonance caused by the two bulb-like resonators The pronounced anticrossing behavior of the splitting peaks can be modified by varying the resonant frequency of MM baffle, the bulb-like resonator's radius and the stub height. Furthermore, it is also found that the Rabi splitting can also be tuned by the separation between resonator and the MM baffle. Such plasmonic waveguide system may have potential applications in providing a stimulating insight to explore new fundamental physics in analogous atomic systems.

1. Introduction

Quantum interferences such as Rabi splitting and Fano resonance in an atomic system have led to several fascinating and extraordinary effects [1–4]. Rabi splitting is of strong interest for studies on light-material interaction effects in recent years and the strong coupling can be observed in the optical spectra with a clear anticrossing behavior [5,6]. Compared with normal mode couplings, Rabi splitting refers in particular to strong coupling in which the coupling strength exceeds the dissipation rates of the system and the energy is therefore coherently exchanged between atom and cavity [7]. As a fundamental resonant effect, the Fano resonance discovered by Ugo Fano, appears as an interference effect between a localized state and a continuum band in quantum or classical systems [4,8–10]. The shape of Fano resonance is distinctly asymmetric, different from conventional symmetric Lorentzian resonance curves. Many parameters of the quantum interference effects are challenging to test in atomic and molecular systems that need sophisticated experimental condition and techniques. Although Rabi splitting and Fano resonance were initially proposed, observed and used in atomic and molecular systems, recently they are among many quantum phenomena that have classical and, more importantly, all optical analogues [8,9,11]. Rabi splitting and Fano resonances have been observed in different systems, including coplanar waveguide [12,13], plasmonic nanoparticles [14], photonic crystals [9], plasmonic nanostructures [4], and electromagnetic metamaterials [8,15]. Many experiments about Rabi splitting have been reported because it has promising applications in the atom detector and infrared photodetectors [16] and it is of great importance for many possible applications in quantum information processing [17]. The specific asymmetric feature of the Fano resonance promises applications in sensors [18], photoluminescence enhancement [19], and so on. The fundamental criterion for a Fano resonance is the interference between a spectrally overlapping broad resonance or continuum and a narrow discrete resonance. These conditions can be easily satisfied using tunable coupled plasmonic structures made of conventional plasmonic materials [8,11]. As an important plasmonic waveguide, metal–dielectric–metal (MDM) configurations attract more and more attention due to their deep subwavelength confinement of light based on surface plasmon polaritons (SPPs) [20–22]. MDM waveguides are regarded as one of the most promising candidates

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for the nanoscale manipulation and transmission of light and offer a pathway for the realization of photonic and quantum functionality in nanostructures [23–25]

In this paper, Fano resonance and Rabi splitting are numerically investigated in a compact plasmonic system, which consists of a MDM waveguide coupled with side cavities and a MM slab baffle. Simulation results show that the side-coupled cavity provides a broadband resonant state and the MM baffle supports a local discrete resonance state, the Fano resonance happens due to the interaction between the two resonant states. For the plasmonic waveguide system with two resonators and one MM baffle, Rabi splitting can occur because of the strong coupling between the narrow spectral response of MM baffle and the Fabry–Perot resonance caused by the two bulb-like resonators. The Fano and Rabi splitting peaks can be easily tuned by varying the resonant frequency of MM, the bulb-like resonator's radius and the stub height. Moreover, Rabi splitting can also be tuned by the separation between resonators and the MM slab baffle without changing the other parameters. The new Rabi splitting formation mechanism, based on the different resonant states, may pave a new route to realize Rabi splitting in the plasmonic structure and may have possible applications in quantum information processing.

2. Bulb-like resonator

The proposed two-dimensional plasmonic waveguide is schematically shown in the inset of Fig. 1(a), consisting of a bulb-like stub side-coupled with the MDM waveguide. The slit width W of waveguide and stub are set to be equal, the radius of the bulb and the length of the stub are denoted by rs and hs, respectively. The blue area represents the insulator dielectric and the circumambience (gray area) is silver, the permittivity of silver as a function of wavelength λ is taken from Johnson and Christy [26] and expanded by using the interpolation method. The transmission spectra of the proposed plasmonic structure are carried out using the commercial finite element method package COMSOL Multiphysics. In the simulations, the fundamental TM mode of the MDM plasmonic waveguide is excited at the left-end of the bus waveguide, shown in inset of Fig. 1(a). As is well known, SPP waves are formed on the two metal interfaces in the two-dimensional MDM waveguide and the dispersion relation of the fundamental TM mode is given by [20]:

$$\frac{\varepsilon_d k_m}{\varepsilon_m k_d} = \frac{1 - \exp(k_d d)}{1 + \exp(k_d d)} \quad (1)$$

where $k_d^2 = \beta^2 - \varepsilon_d k_0^2$, $k_m^2 = \beta^2 - \varepsilon_m k_0^2$, β is the propagation constant of SPP, $k_0 = 2\pi/\lambda$ is the wave number of light in the air, λ is the wavelength of incident wave. ε_d and ε_m are the permittivities of the dielectric core and metal material, respectively. In all of the structures, the dielectric core is assumed to be air. The effective refraction index of the MDM waveguide is defined as $n_{eff} = \beta/k_0$, which can be calculated by Eq. (1). In all the simulations, the width of the MDM waveguide is fixed at $W = 50$ nm (much smaller than the wavelength) to ensure that only the fundamental transverse magnetic mode is supported [27]. For a MDM waveguide with a bulb-like stub, the localized resonance can be excited when the incident light approaches the intrinsic resonance frequency, which works as a Fabry–Perot resonator or cavity [25]. The resonance condition is $2n_{eff}L_{eff} \approx m\lambda$, where m is the resonance order, e.g. $m = 1$, 2, 3 correspond to the first, second and third order resonance mode, L_{eff} is the effective length of the bulb-like resonator which changes with hs and rs.

Fig. 1(a) shows the transmission spectra of the bulb-like resonator with different radius rs. The transmission spectra plotted in black short dash dot, blue short dot, magenta, and olive short dash lines correspond to the radii of 25 nm, 30 nm, 35 nm and 40 nm, respectively, where $hs = 60$ nm. These single stub resonators yield a broadband stop spectrum with a resonant wavelength of $\lambda = 608$ nm, 731 nm, 823 nm, 906 nm, respectively, which exhibit red shift as the radius increases.

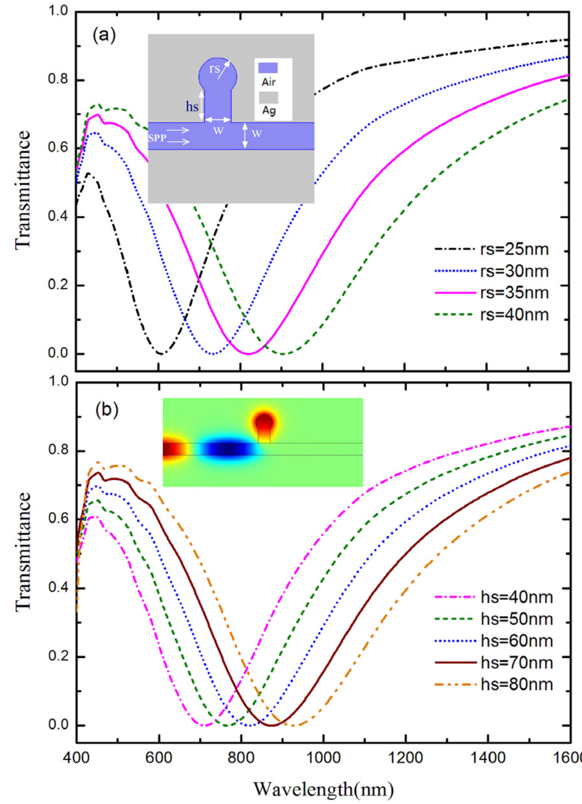

Fig. 1. Transmission spectra of the plasmonic MDM waveguide side-coupled a bulb-like resonator with various radius of rs (a) and different stub height of hs (b), where the slit width is of $W = 50$ nm, in (a) $hs = 60$ nm and $rs = 35$ nm in (b). The inset in Fig. 1(a) is the schematic of the resonator, the inset in Fig. 1(b) is the magnetic field distribution of the resonator system at the resonant wavelength $\lambda = 731$ nm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

And the bandwidth of $\Delta\lambda_{\mathrm{FWHM}}$ is about 303 nm, 400 nm, 468 nm, 460 nm, respectively, which indicates that the resonant modes possess large damping. In addition, the loss of the metal is inevitable, so all the transmittances do not reach unity. Fig. 1(b) shows the transmission spectra of the waveguide cavities with various stub heights of hs = 40 nm, 50 nm, 60 nm, 70 nm and 80 nm respectively, where rs = 35 nm, the maximum transmittance is about 85% in the wavelength of interesting. It is found that the wavelength of the transmission dips also exhibit red shift as hs increases. The characteristics of the single stub resonator typically exhibit broadband transmission spectra with nearly symmetric Lorentzian-like line shapes [25]. At the resonant wavelength (such as $\lambda = 731$ nm, the blue short dot line in Fig. 1(a)), the magnetic field distribution as shown in the inset of Fig. 1(b) demonstrates a typical first order resonance mode of the bulb-like stub resonator, where there is anti-phase between the resonator and MDM waveguide.

3. Fano resonance with two different resonators

The results aforementioned indicate that the resonant modes exist in the bulb-like resonator and their resonance wavelengths can be changed by altering the geometric parameters such as the hs and rs. For such a plasmonic structure involving coupling of one or several cavities to a waveguide, the Fano resonance effect naturally exists [18,28]. The sharp Fano resonances in the coupling systems, sometimes behaving like coupled resonator induced transparency [29,30], where the Lorentzian line shape can be dramatically deformed by coupling the two individual microcavities. In general, the coupled resonator structures have two typical geometries: directly and indirectly coupled resonators [31]. To