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Analysis of the transmission properties of symmetry/symmetry broken waveguide systems

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ABSTRACT

We investigate for the first time the effects of a bar on the non-periodic waveguide system, which consists of a wide gap metal–insulator–metal (MIM) structure intermediately connecting with a narrow gap MIM waveguide, by means of the finite element method. Simulation results show that the introduction of a metallic bar enriches the transmission spectra. As the bar has more influence on the electric (magnetic) field in the wide gap MIM waveguide, the transmission peaks exhibit red-shift (blue-shift), in comparison with the corresponding resonant wavelength without the bar. These phenomena can be well explained by the surface charge and current model. In addition, we propose a fitting formula to reveal the relationship between the resonant wavelength and the parameters of the structure. All of the calculated results match the model and the new fitting formula very well. Moreover, when the symmetry of the structure is breaking, the anti-symmetric waveguide mode of the wide gap MIM waveguide is excited. Then the interference of the narrow trapped resonance and the broad Lorentzian-like resonance based on different waveguide modes (anti-symmetric mode and the symmetric mode) gives rise to a Fano resonance in the broken plasmonic resonator. The mechanism based on different waveguide modes paves a new route to realizing Fano resonance in the plasmonic waveguide system. The utilization of the fitting formula and anti-symmetric mode in the MIM waveguide provides a new possibility for designing high-performance plasmonic devices.

1. Introduction

The effect of defects in periodic silts on the optical transmission [1–3] has attracted the attention of many scholars since Ebbesen et al. [4] reported the enhanced transmission through a sub-wavelength hole array in a metallic film. Wang et al. investigated the transmission through metallic array slits with perpendicular cuts [1]. The existence of the cuts in the different positions of the slits causes the resonant wavelength to change non-monotonically. The authors of the present paper propose a surface charge and current model to explain these phenomena. In addition, Zhai et al. [2] and Guo et al. [3] also proposed structures to study the effects of the defects on the optical transmission. As of yet, most researchers have placed their emphasis on periodic slit arrays [1] or cuts [2–3]. However, the size of the mentioned structures [1–3] is very large due to the periodicity, and the dependence of transmission on the size or position of defects has yet to be investigated systematically.

Small size and easy integration are the inevitable trends in the future development of optical communication. Surface plasmon polaritons (SPPs) are considered to be the most promising candidate for the realization of highly integrated optical circuits, due to their capability to overcome the diffraction limit of light [5]. As a fundamental resonant effect, the Fano resonance, which arises from the interference between a localized state and a continuum band [6,7], has been widely studied in numerous nanostructures, such as planar oligomers [8,9], nano-disk/ring [10–12], and MIM waveguide [13–16]. Among all the nanostructures, the MIM waveguide structures have attracted many researchers attention because these structures exhibiting more suitable for the highly integrated optical circuits due to their deep-sub-wavelength confinement of light [17–20]. Different from the Lorentzian resonance, the Fano resonance exhibits a typical sharp and asymmetric line profile [7], and this specific feature of the Fano resonance promises applications in many plasmonics devices [21–24]. Therefore, combining the Fano resonance with plasmonic structures would create the possibility of achieving ultracompact functional optical components for use in highly integrated optics [25].

In this paper, we introduce a bar to tune the transmission spectra by means of a plasmonic resonator, which comprises a

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wide gap MIM structure intermediately connecting to a narrow gap MIM waveguide. It is found that the introduction of the bar enriches the transmission spectra, and that the transmission spectra are sensitive to the parameters and position of the bar due to the influence of the bar on the surface charge and current in the wide gap MIM structure. When the bar has a greater influence on the electric field in the wide gap MIM waveguide, the transmission peaks exhibit red shift, and when the bar has a greater influence on the magnetic field, the transmission peaks display blue shift. In addition, we also propose a new fitting formula to reveal the relationship between the resonant wavelength and the parameters of the structure. When the symmetry of the structure is broken, the anti-symmetric waveguide mode of the wide gap MIM waveguide is excited. Then the interference of the narrow trapped resonance and the broad Lorentzian-like resonance based on different waveguide modes (anti-symmetric mode and symmetric mode) gives rise to the Fano resonance in the broken plasmonic resonator. The mechanism based on different waveguide modes creates a new path to realizing Fano resonance in the plasmonic waveguide system.

2. Structure and simulations

Fig. 1(a) schematically shows the proposed plasmonic waveguide structure. The white and blue parts denote air ($\varepsilon_d = 1.0$) and Ag (ε_m), respectively. The metal bar (width of d and height of h) placed in the wide gap MIM structure is designed to investigate its effect on the optical transmission. The thicknesses of the wide dielectric gap and narrow dielectric gap are T and t, respectively. The length of the wide gap MIM structure is L, and Δ is defined as the distance from the center of the bar to the center of the wide dielectric gap. The transmittance of SPPs at port b is defined as the quotient between the SPPs power flows of port b and port a. The power flows at the ports are obtained by integrating the Poynting vector over the channel cross-section [24].

In order to investigate the influences of the bar, we first investigated the transmission spectrum of the proposed structure without the bar, using the finite element method (FEM) of COMSOL Multiphysics. In the simulations, the parameters are set as follows: $L = 500$ nm, $T = 500$ nm and $t = 50$ nm (these parameters are fixed throughout this paper). The permittivity of Ag is characterized by the Drude model: $\varepsilon_m = \varepsilon_\infty - \omega_p^2/(\omega^2 + i\omega\Gamma)$ with $\varepsilon_\infty = 3.7$, $\omega_p = 9.1$ eV, $\Gamma = 0.018$ eV [13,23]. The transmission spectrum is shown in Fig. 1(b), and the transmission peak in the transmission spectrum is at $\lambda_0 = 1104$ nm. The contour profile of field $|H_z|$ of the device at $\lambda_0 = 1104$ nm is shown in Fig. 1(c). The wide gap MIM structure simply acts as an F–P cavity. These simulation results agree well with the results in Refs. [26,27].

3. The effect of the bar on the optical system

As can be seen from Fig. 1(a), the proposed structure shows two different symmetry features due to the presence of the bar. When $\Delta = 0$, the original symmetry of the system is unchanged; on the other hand, the symmetry of the system is broken when $\Delta \neq 0$. These two situations may display different transmission properties. In order to understand the effects of the bar on the optical system, in the following section the two different symmetry features are investigated one by one.

For the sake of simplicity, we begin with the symmetrical structure, in which $\Delta = 0$. We fixed the height of the bar $h = 100$ nm, then varied the width d. The calculated transmission spectra are displayed in Fig. 2(a). For a better observation, we plotted the relationship between the resonant wavelength and the width of the bar d, as shown in Fig. 2(b). It is clearly observed that the transmission spectra first show a red shift then a blue shift at the turning point of about $d = 250$ nm. Remarkably, the resonant wavelength does not change monotonically, which depends on the width of the bar.

In order to obtain greater insight into the above behaviors of

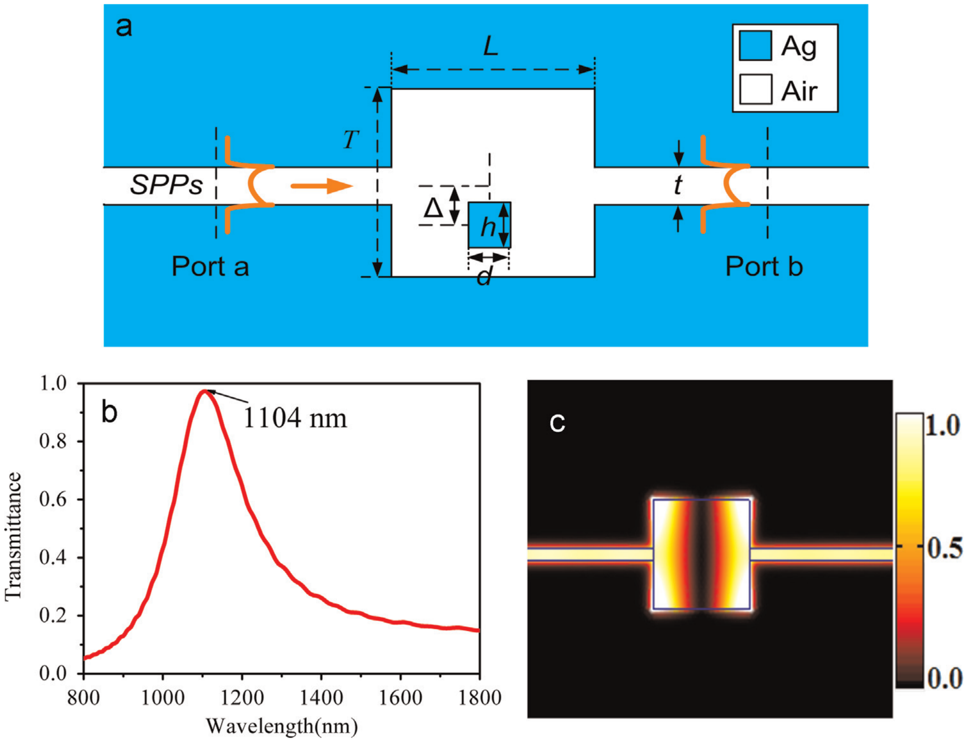

Fig. 1. (a) Schematic configuration and geometric parameters of the plasmonic waveguide system. (b) Transmission spectrum of the structure without the bar. (c) The contour profiles of field $|H_z|$ of the device at $\lambda = 1104$ nm.