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# Evolution of Fano resonance based on symmetric/asymmetric plasmonic waveguide system and its application in nanosensor

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We proposed a plasmonic nanosensor based on Fano resonance in the symmetric and asymmetric plasmonic waveguide system, which comprises with a rectangular cavity and two slot cavities with the metal-dielectric-metal waveguide. Simulation results show that by symmetric/asymmetry rectangular cavity and regulating the rectangular cavity coupling with slot cavities, different waveguide modes can be excited. Due to the interaction of the waveguide mode, the transmission spectra possess single, double or multiple sharp asymmetrical profiles. Because of the different origins, these Fano resonances exhibit different dependence on the parameters of the structure and can be easily tuned. These characteristics offer flexibility to design the device. This nanosensor yields a sensitivity of ~800 nm/RIU and a figure of merit of about $\sim 1.35 \times 10^4$, which can find widely applications in the plasmonic nano-sensing area.

## 1. Introduction

Surface plasmon polaritons(SPPs) are regarded as the most promising candidates for the realization of highly integrated optical circuits, due to their capability to overcome the diffraction limit of light [1]. Recently, some novel physical features enabling the miniaturization of optical devices have been investigated in various plasmonic nanostructures, such as waveguide [2–4], metamaterials [5]. Among all the nanostructures, the metal-dielectric-metal (MDM) waveguide based on SPPs has deep subwavelength field confinements and low bend loss, and thus, it has important applications in highly integrated photonic circuits [6–10]. Based on the MDM waveguide, a large number of devices, such as splitters [11–13], filters [14–17], sensors [2,18,19], and demultiplexers [13,20,21] have been designed and demonstrated in theory and experiment. As a fundamental resonant effect, the Fano resonance, originates from the interference effect between a localized state and a continuum band in quantum or classical systems [22,23]. Recently, many plasmonic structures have been designed to achieve the Fano resonance. Usually, using asymmetric plasmonic structure is a common way to obtain the Fano resonance such as the symmetry-breaking T-shape double slit [24], the broken symmetry in disk cavities or the ring [25,26], asymmetric stub pair in Metal- dielectric -metal (MDM) waveguide [27,28]. Besides, the Fano resonance also be achieved in the symmetric plasmonic structures, including cavity–cavity interference [2–4], nanoslits in a metallic membrane [29], waveguide-coupled resonators [30]. Different from the Lorentzian resonance, the Fano resonance exhibits a typical sharp and asymmetric line profile [20], which has great important applications in demultiplexing [21], plasmonic switch [22], and so on. The specific feature of Fano resonance promises applications in sensors [19], such as Lu et al. designed a dual resonator structure to achieve a plasmonic nanosensor [4], Chen et al. designed a stub and groove resonator to achieve a refractive index sensor [18]. Therefore, combining the Fano resonance with MDM plasmonic structures would create the possibility of achieving ultracompact functional optical components for use in highly integrated optics [31].

In this paper, a MDM-waveguide structure is proposed to realize the Fano resonances in the symmetric or asymmetric plasmonic structure. In our proposed symmetric plasmonic structure, two identical slot-cavity resonators are placed close to the ends of the rectangular cavity, which symmetrically locate at both sides of a MDM bus waveguide. Simulation results show that the two sharp and asymmetric transmission profiles are formed with interaction of the narrow discrete spectrum and a broad continuous spectrum caused by the slot cavities and the rectangular cavity,

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respectively. The asymmetrical line shape and the resonant wavelength can be easily tuned by changing the geometrical parameters of the structure. Meanwhile, we extend this plasmonic structure by asymmetric rectangular cavity or the regulating rectangular cavity coupling with the slot cavities for the more investigations. Simulation results show that a new sharp asymmetrical line shape appears and can be easily tuned. The proposed structure can serve as an excellent plasmonic sensor with a sensitivity of ~800 nm/RIU and a figure of merit of about $1.35 \times 10^4$, which can find widely applications in the plasmonic nano-sensing area.

## 2. Symmetric rectangular cavity coupling with the slot cavities

Fig. 1(a) shows the two-dimensional geometry of the symmetric plasmonic structure composed of a MDM waveguide and two identical slot-cavity resonators, which is placed close to the ends of the rectangular cavity. The width and height of the rectangular cavity are denoted as $W$, $H$ ($H1+H2+W1$) and $\triangle H = H1 - H2$, respectively. Meanwhile, the coupling distances from the rectangular cavity to the slot cavities are $g$. $W1$ and $L$ are the width and length of the slot cavities, and the width of the MDM waveguide is also $W1$. Here, the value $W1=50$ nm and $g=10$ nm are fixed throughout this paper. The white and blue parts denote air ($\varepsilon_{air}=1.0$) and Ag ($\varepsilon_m$), respectively.

In order to investigate the optical responses of the proposed structure, its transmission spectra are numerically calculated by using the finite element method (FEM) of COMSOL Multiphysics. The transmittance of SPPs is defined as the quotient between the SPP power flows (obtained by integrating the Poynting vector over the channel cross-section) of the observing port with structures (rectangular cavity and slot-cavity resonators) and without structures [11,18,19,24]. The permittivity of Ag is characterized by the Drude model:

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

Here, $\varepsilon_\infty$ is the dielectric constant at the infinite frequency and $\omega_p$ and $\gamma$ stand for the bulk plasma frequencies and the electron collision, respectively. $\omega$ is the angular frequency of incident light. The parameters for silver can be set as $\varepsilon_\infty$=3.7,$\omega_p$=9.1$eV$ and $\gamma$ = 0. 018eV [32]. The parameters of the proposed structure are set as: $L=550$ nm, $H=345$ nm, $\triangle H=0$ and W1=225 nm and the calculated transmission spectra are displayed in Fig. 1(b). It is found that the transmission spectrum in the plasmonic waveguide system exhibits two sharp and asymmetric resonant peaks, which are typical Fano-like profiles [2,11,18]. This is quite different from the symmetric Lorentzian transmission line shape. Here, we called the left peak of the Fano resonance of FR1, correspondingly, the right peak of the Fano resonance is FR2, for description conveniently. Clearly, the two Fano peaks drop sharply from the peak to the dip in the spectra.

In order to understand the underlying physics of the resonant peaks in the transmission spectra, the field distributions of $|H_z|^2$ at $\lambda=706$ nm and $\lambda=869$ nm, corresponding to the FR1 and FR2, are displayed in Fig. 1(c)–(d), respectively. Because the input light is set to be transverse magnetic (TM) plane wave, the resonant modes can be classified using $TM_{mn}$ [25], m, n are integers and indicate the $x$-directional and $y$-directional resonant orders, respectively. Obviously, at $\lambda=706$ nm, the system shows a relatively complicated interference phenomenon with $TM_{10}$ mode in the rectangular cavity and $TM_{30}$ mode in the two identical slot cavities, as can be seen in Fig. 1(c). On the other hand, at $\lambda=869$ nm, almost all the energy confined in the slot cavities with $TM_{20}$ mode, indicating a relatively simple interference phenomenon, as can be seen in Fig. 1(d). Here, we can make a simple inference that FR1 is influenced both by the slot cavities and the rectangular cavity, while FR2 mainly affected by the slot cavities.

As we know, in a plasmonic resonator, the accumulated phased shift per round trip for the SPPs is $\phi = 4\pi n_{eff} S/\lambda + 2\varphi$ [15,34]. Constructive interference should occur when$\phi = 2N\pi$, and thus the resonant wavelength is determined by

$$\lambda = \frac{2n_{eff}S}{(N - \varphi/\pi)} \tag{2}$$

where $n_{eff}$ denotes the effective index of the SPPs, which can be obtained by solving the eigenfunction in the MDM waveguide [35].

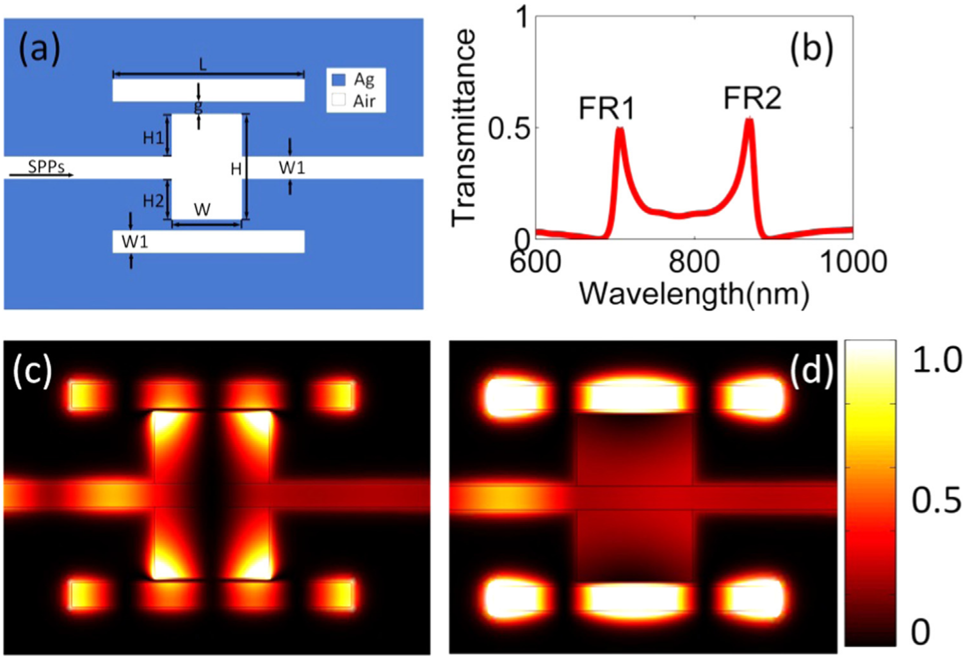

**Fig. 1.** (a) Schematic configuration and geometric parameters of the plasmonic waveguide system. (b) Transmission spectra of the plasmonic waveguide system: the parameters are set as $L=550$ nm, $\triangle H=0$ and $W1=225$ nm. (c and d) The $|H_z|^2$ field distributions at the resonance wavelength $\lambda=706$ nm and $\lambda=869$ nm.