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# Sensing characteristics based on Fano resonance in rectangular ring waveguide

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ABSTRACT

Sensing characteristics based on Fano resonance in a rectangular ring resonator with a stub are investigated numerically. Simulation results show that a sharp and asymmetric Fano-line shape emerges in the proposed structure. Through tuning the width and length of the stub, it is found that the width and length play an important role in optimizing the sensing characteristic. Using the sharp and asymmetric Fano-line shape a highly sensitive plasmonic nanosensor with the sensitivity of 1000 nm/RIU and a tunable figure of merit (FOM) can be attained. The maximum FOM can reach up to 992,800 when the stub length $d=120$ nm, width $l=130$ nm and the refractive index difference $\Delta n=0.05$, which is larger than that in previous reports. In addition, the results show that a larger FOM can be obtained by tuning the stub width than tuning its length. The proposed model and results provide guidance for fundamental research of the plasmonic nanosensor applications and designs.

## 1. Introduction

Surface Plasmon Polaritons (SPPs), known as controlling light at the nanoscale due to their capability to overcome the diffraction limit [1], has attracted enormous researches, such as the biomedicine [2], optical filter [3], solar cell [4], and so on. A metal–dielectric–metal (MDM) waveguide, which supports the propagation of SPPs in the metal–dielectric interface and manipulates light on a subwavelength scale can be regarded as an ideal integrated photonic device [5–6]. Applications based on MDM waveguide have been widely reported, such as plasmon induced transparency (PIT) [7–10], optical switch [11], slow light devices [12–15], plasmonic waveguide filters [16–20], and plasmonic sensors [21–24].

Recently, Fano resonances have been also observed in MDM waveguides, which are known as a fundamental resonant effect, discovered by Ugo Fano [25], originate from the interference of the discrete state and continuum state [26], and possess a distinctly sharp and asymmetric line profile. The specific feature of the Fano resonance has shown great sensitivity and larger figure of merit (FOM) and has promising applications in sensors. Lu et al. reported an MDM waveguide side-coupled with a pair of nanoresonators with a sensitivity of about 900 nm/RIU and a FOM of about 500 [22]. Chen et al. showed a rectangular ring metal–insulator–metal waveguide with a baffle and achieved a FOM of about 6838 [24]. Nevertheless, these researches mainly focused on the sensing property of specific structure parameters; the sensing optimization based on tuning the structure parameters is seldom discussed.

In this paper, a rectangular ring resonator loaded with a stub is proposed and the optical transmission properties of the structure are investigated numerically by the Finite Difference Time Domain (FDTD). Simulation results show that a sharp and asymmetric Fano resonance line-shape can be obtained. Through tuning the length ($d$) and width ($l$) of the stub and the refractive index ($n$) of the dielectric, FOM is investigated in the proposed MDM waveguide structure in detail. The results show that FOM changes with $d$, $l$ and $\Delta n$. The structure can work as an excellent plasmonic sensor with a sensitivity of about 1000 nm/RIU and a FOM of about 992,800 when $d=120$ nm, $l=130$ nm, and $\Delta n=0.05$ at $\lambda=1088$ nm, which is larger than that in previous reports [22,24]. The results show that a larger FOM can be obtained by tuning the stub width than by tuning its length.

## 2. Structure and simulations

The proposed MDM waveguide structure, which consists of a rectangular ring resonator coupled with a bus waveguide, is schematically shown in Fig. 1(a). A stub is loaded in the middle of the horizontal branch of the rectangular ring resonator. Fig. 1(b) shows the 2-dimensional schematic structure of Fig. 1(a), where the turquoise and white areas represent Au and air, respectively. The width of the bus waveguide and the rectangular

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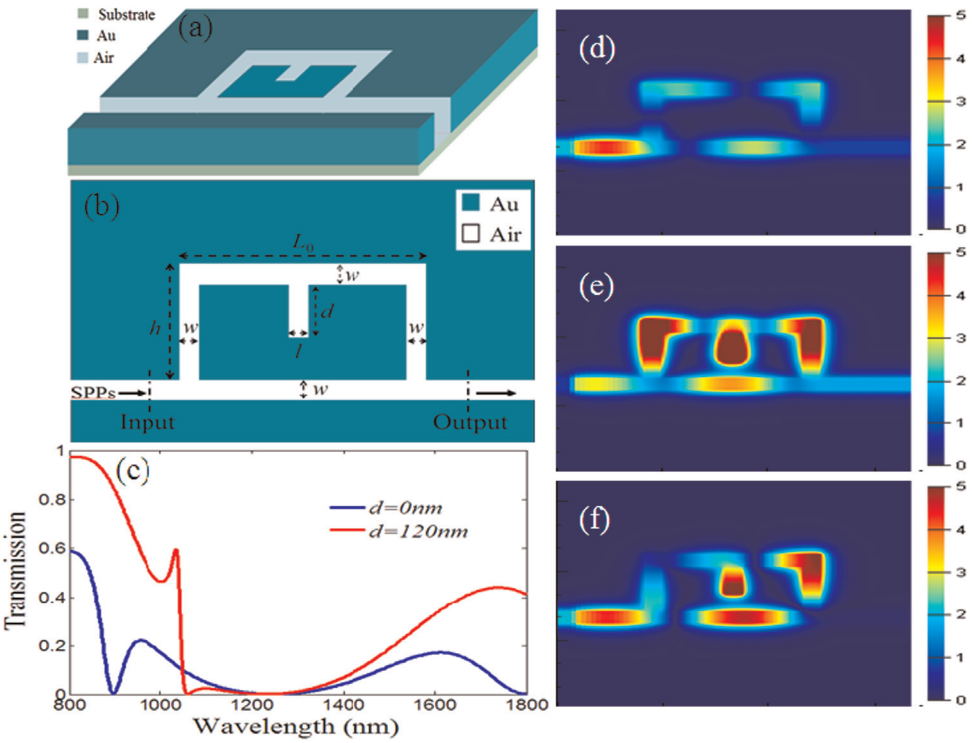

**Fig. 1.** Schematic of the rectangular ring resonator with a stub: (a) 3-dimensional. (b) 2-dimensional. (c) Transmission spectra of rectangular ring resonator without a stub (blue curve) and with a stub with width $l=50$ nm, length $d=120$ nm (red curve). (d) Magnetic field distribution of structures without stub at $\lambda=1033$ nm. Magnetic field distribution of structures with stub: (e) $\lambda=1033$ nm. (f) $\lambda=1061$ nm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ring resonator is $w$, and the length and height of the rectangular ring are $L_0$ and $h$, respectively. $l$ and $d$ represent the width and length of the stub, respectively.

The properties of Fig. 1(b) are numerically investigated using the two-dimensional FDTD method. When an incident pulse is input, the propagating SPP wave, which is confined in the metal–dielectric interface, may be coupled into the rectangular ring resonator and the stub. In the simulation, the permittivity $\varepsilon_m$ of Au can be approximately defined by the Drude model: $\varepsilon_m(\omega)=\varepsilon_\infty-\omega_p/(\omega^2+i\omega\gamma_p)$, where $\omega$ stands for the angle frequency of the incident wave, $\varepsilon_\infty=3.7$, $\omega_p=1.37\times10^{16}$ rad/s is the bulk plasmon frequency, and $\gamma_p=4.08\times10^{13}$ rad/s stands for the damping rate, which characterizes the absorption loss. These values are obtained by fitting the experimental results [27]; the parts colored in white are chosen to be air with permittivity $\varepsilon_0=1$ for simplicity. Optical transmission properties of the proposed structure are investigated in time domain when fix $w=50$ nm, $L_0=500$ nm, and $h=250$ nm. Transmission spectra of the plasmonic waveguide are tuned by adjusting the width and length of the stub. Transmittance is calculated by $T=P_{out}/P_{in}$, where $P_{in}$ and $P_{out}$ stand for the input and output power, respectively.

The transmission spectra of the structure without and with a stub are shown by the blue and red curves in Fig. 1(c), respectively. It is clear that the transmission spectrum (blue curve) becomes sharp and asymmetric (red curve) when the structure is loaded by a stub ($l=50$ nm, $d=120$ nm). For the asymmetric spectra, the transmittance of the SPPs varies sharply from the peak to valley with a small wavelength shift. The field distributions of the peak ($\lambda=1033$ nm) and the valley ($\lambda=1061$ nm) are displayed in Fig. 1(e) and (f), respectively. The field distribution of the structure without stub at $\lambda=1033$ nm is displayed in Fig. 1(d). At $\lambda=1033$ nm, when without the stub, most of the power is reflected back to the input, and almost no power transports to the output. On the contrary, when loaded with a stub, strong field distributions are obviously observed in the rectangular ring resonator and the stub, a part of power transports to the output. The resonant mode of the rectangular ring is changed by the stub. At $\lambda=1061$ nm, there are also no power transports to the output, most of which is trapped in the rectangular ring resonator and the stub; the others are reflected back to the input.

## 3. Transmission characteristics and analysis

As shown in Fig. 1(d)–(f), the incident light waves can be reflected back and forth in the proposed structure, the rectangular ring resonator, with the stub just like an FP resonator, which results in a sharp and asymmetric Fano resonance [26]. The accumulated phase delay per round trip in this FP resonator is $\Delta\varphi=k(\omega)\cdot2(L+d)+\theta$, where $k(\omega)=2\pi\cdot n_{eff}/\lambda$ is the angular wave number at frequency $\omega$, $L$ is the effective length of rectangular ring, $\theta$ is the phase shift brought by the reflection in the resonator and $n_{eff}$ is the effective refractive index of the SPP mode in the resonator. When $\Delta\varphi=m\cdot2\pi$ ($m$ is an integer), the resonance wavelengths $\lambda_m$ can be expressed as

$$l_m = 2n_{eff} \times (L + d)/(m - q/2p) \tag{1}$$

It is worth noting that $n_{eff}$ and $L$ are related to the resonance wavelength $\lambda_m$ and play an important role in controlling resonance wavelength and transmission in this structure.

The evolution of transmission characters is depicted in Fig. 2. Fig. 2(a) shows the Fano resonance wavelength has a red-shift with the increment of the stub length from 110 nm to 140 nm when the width is fixed at $l=50$ nm. This phenomenon can be explained by Eq. (1); with the increase of stub length $d$, the effective length of the resonator increased, which means $\lambda_m$ became larger. Fig. 2(b) shows the resonance wavelength has a blue-shift