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High sensitivity plasmonic sensing based on Fano interference in a rectangular ring waveguide

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ABSTRACT

We investigate a plasmonic waveguide system using 2-dimension finite element method, which consists of a rectangular ring metal–insulator–metal waveguide and a baffle. Numerical simulations results show that the sharp and asymmetric Fano-line shapes can be created by the proposed structure, because of the interaction between the strong trapped resonance in the FP resonator and the weak resonance in the stub resonator. An analytic model based on the scattering matrix theory is utilized to describe and explain this phenomenon. The physical features contribute to a highly efficient plasmonic nanosensor for refractive index sensing with the sensitivity of 1300 nm/RIU and a figure of merit of 6838. This plasmonic structure with such high figure of merits may find important applications in the on-chip nanosensors.
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1. Introduction

Electromagnetic waves coupled to collective oscillations of free electrons in a metal, known as surface plasmon polaritons (SPPs), has regarded as the most promising way for realization of highly integrated optical circuits, and has attracted great attentions in recent years [1,2]. A large number of devices based on SPPs have been investigated and analyzed theoretically and experimentally, such as plasmonic slot waveguides [3], all-optical switches [4], and Mach–Zehnder interferometers [5]. Among them, the metal–insulator–metal (MIM) structure has attracted more and more attention due to their deep-subwavelength confinement of light [6], and has wide applications in deep-subwavelength optical devices, such as filter [7], the absorption switches [8], Y-bend combiner [9], and plasmonic electro-optical switching [10]. As a fundamental resonant effect, the Fano resonance, which arises from the interference between a localized state and a continuum band [11], has been widely known in numerous physics systems, such as metamaterials [12], a metallic nanodisk [13], and pentamers [14]. Different from the Lorentzian resonance, the Fano resonance exhibits a typical sharp and asymmetric line profile [15], which has great important applications in demultiplexing [16], plasmonic switch [17], and so on. The specific feature of Fano resonance promises applications in sensors [18]. Thus, combining the Fano resonance with plasmonic structures would open the possibility to achieve ultracompact functional optical components in highly integrated optics [19]. The devices based on the Fano resonance show high sensitivity and a large figure of merit (FOM) due to the microscopic origin as an interference phenomenon and the unique line shapes of the Fano resonance, which can be used in sensors, lasing, switching, and nonlinear and slow-light devices.

In this paper, a rectangular ring MIM waveguide with a metal baffle is proposed and the properties of the structure are investigated numerically by the finite element method (FEM). Simulation results show that sharp and asymmetric Fano-line shape emerges in the plasmonic structure, when the baffle is put into the rectangular ring. Due to the presence of the baffle, new stub resonators are formed in the rectangular ring, and the two stub resonators with the connection waveguide are proposed as an F–P resonator. The interaction between the strong trapped resonance in the FP resonator and the weak resonance in the stub resonator gives rise to the Fano resonance. This phenomenon can be well explained by the scattering matrix theory. The proposed structure is expected to work as an excellent plasmonic sensor with a sensitivity of about 1300 nm/RIU and a FOM of about 6838.

2. Structures and simulations

The proposed plasmonic waveguide structure is schematically shown in Fig. 1(a), the sketch of the plasmonic structure is

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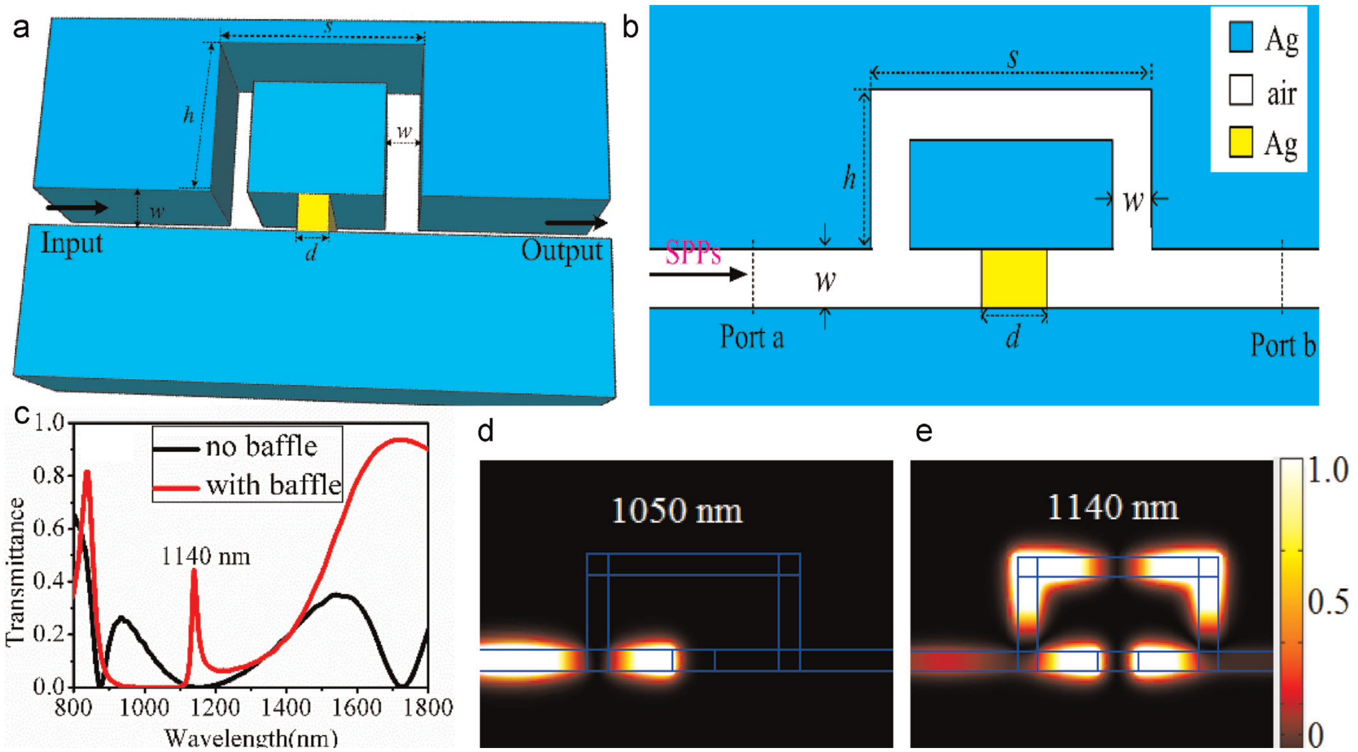

Fig. 1. Schematic of the rectangular ring MIM waveguide with a baffle and the geometrical parameter symbols: (a) 3-dimension, (b) 2-dimension. (c) Transmission spectra of port b without baffle (black curve) and with baffle (red curve), respectively. Corresponding field distributions (|Hz|) of the optical system with $d=100$ nm at the incident wavelength (d) 1050 nm, (e) 1140 nm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

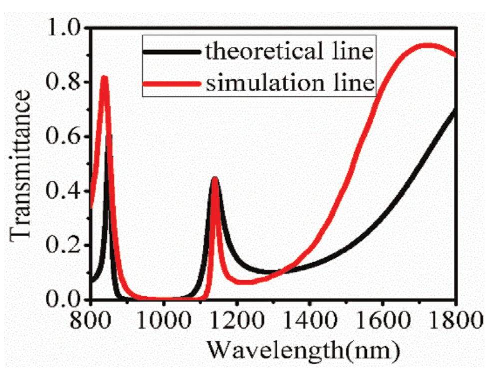

Fig. 2. Transmission spectra of analytic model result (black line) and simulation result (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

composed of a rectangular ring MIM waveguide and a baffle. Fig. 1 (b) shows the 2-dimension schematic structure of Fig. 1(a). The baffle can be metals or dielectric with high refractive index. This system is a two-dimensional model, and the blue, white and yellow areas are chosen to be Ag, air and Ag, respectively. Without the baffle, the power flow of SPPs goes to port b in two directions and will interfere with each other. With the baffle, the proposed structure formed a stub resonator on each side of the baffle, the two stub resonators would affect and coupled with each other through the connection part of the MIM waveguide, which may affect the transmission spectra significantly.

The properties of Fig. 1(b) are numerically investigated using the finite element method (FEM) with Comsol Multiphysics. Since the width of the bus guide is much smaller than the wavelength of the incident light, only a single propagation mode TM_0 can exist in the structure. Therefore, when a TM-polarized plane wave is injected into the MIM structure, the incident light will be coupled

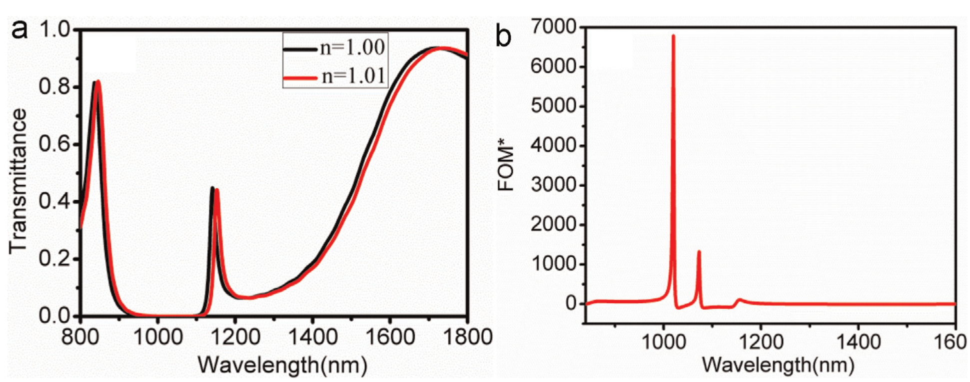

Fig. 3. (a) Transmission spectra obtained by FEM simulation for different refractive index (n). (b) Calculated FOM* at different wavelengths. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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