The Study of Plasmonic Biosensors based on Mach-Zehnder Interferometry

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ABSTRACT— Fano resonance is a branch of surface plasmonics that has become a hot topic in sensing due to its asymmetric response spectrum, field enhancement effect and high sensitivity to refractive index (RI). In this research a plasmonic biosensor has been designed and simulated based on Mach-Zehnder interferometer. The simulations show that, the designed biosensor is able to detect changes of the RI of the surrounding media. The refractive indices (RIs) selected in this paper cover a wide range of RIs for biological samples. However, it is possible to accommodate media with RIs other than those in this specific range. The biosensor's sensing performance embedded in the sample has been tested in different conditions. Different frequencies can be achieved by changing the sample RI.

KEYWORDS: Biosensor; Fano Resonance; Mach-Zehnder Interferometer; Plasmonic; Sensitivity; Surface-Plasmon-polariton

I. INTRODUCTION

A wide range of applications is possible with surface plasmonic sensing technology, including biology, chemistry [2], security[3], medical analysis [4] and drug development[5]. Different types of plasmonic sensors exist, including temperature sensors, phase sensors[6], and refractive index sensors [7]. The interest in refractive index (RI) plasmonic sensors stem from their ability to measure refractive index changes in surrounding media using surface-plasmon-polaritons (SPPs) [8]. In metals, surface plasmon polaritons (SPPs) are propagating excitations that result from electron collective oscillations coupled with light [9]. At the two-dimensional (2D) interface, SPPs are strongly localized at the metal/dielectric interface [10, 11], thus enhancing the intensity of the SPPs. As a result, the SPPs are very sensitive to the state of the interface [9]. Therefore, SPPs localize on the surface due to the exponential decay of their electromagnetic fields[9]. A key capability of SPPs is the sub-wavelength confinement of electromagnetic (EM) energy at interfaces, which makes them suitable for applications as miniature plasmonic devices like sensors [7]. At the interface of media with positive and negative EM susceptibilities are required to propagate SPPs [12,13]. A Plasmonic RI sensor can be constructed with different structures such as Mach–Zehnder Interferometers (MZIs) [14], Y-shape structures [15], and photonic crystals [16]. The advantage of MZI-based plasmonic sensors is that they can develop ultrahigh-sensitivity subwavelength devices in the infrared range of frequencies [17]. In addition, it is easy and cost-effective to manufacture of MZI's products [18-20]. Due to the high sensitivity of the Mach-Zehnder interferometers [13], they can be used in a variety of applications like sensing platform. By using MZI plasmonic biosensors, various samples with different RIs, including cancer cells, can be detected [21].

Fano resonance is a branch of surface plasmonics that has become a hot topic in sensing subject due to its asymmetric response spectrum, field enhancement effect, and high sensitivity to refractive index [22, 23]. A Fano resonance occurs when dark narrowband molds and bright broadband molds are coupled in the structure. Unlike the traditional Lorentz line, the Fano resonance is very sensitive to the surroundings and structural parameters. Since it can achieve higher sensitivity, it is deeply concerned with the refractive index [24, 25].

A plasmonic RI biosensor employing an asymmetric MZI coupled with a ring resonator is presented here. The coupling of the resonator and the MZI, causes Fano resonance. This MZI consists of a waveguide with lossy dispersive media interfaces with a sample and provides EM energy confinement and a long propagation length for SPPs. Here, a novel configuration of the biosensor structure is presented to increase its applicability and function. This biosensor structure can be used to identify a variety of samples.

II. Model

We design an MZI-based plasmonic RI biosensor. Due to their inherent subwavelength confinement, SPPs are commonly used in biosensors. The designed plasmonic biosensor structure is composed of an asymmetric MZI made of a slab waveguide coupled to a ring resonator. Silver is used as the dispersive medium in the waveguide cladding and the sample fills the core and the resonator. Biosensor structure is shown in Fig. 1. It shows an input laser applied to the waveguide's input port. Linearly polarized laser signal with E = 50V/m is used as the input signal. SPPs propagate along the structure due to the coupling between incident EM radiation and oscillating electrons at the interface. MZI 's output spectra are then analyzed.

Fig. **1** Schematic of the configuration of biosensor made of plasmonic waveguide in MZI coupled to a ring resonator. The gray and yellow areas are dispersive media (silver) and sample, respectively.

The biosensor sensitivity is analyzed for different RIs of the sample. We chose samples with RIs ranging from 1.33 to 1.4 to demonstrate the sensitivity of the biosensor. Based on these descriptions, Sec. 3 presents numerical results. The finite element method (FEM) with scattering boundary conditions is employed to simulate and research the sensing characteristics. In the FEM, the optical waveguide is divided into discrete elements or subdomains. In this project we used COMSOL software to simulate our system.

III. Results and discussion

Here, the simulation results for our plasmonic biosensor are presented. We are able to detect changes in the RI of the surrounding media using our plasmonic biosensor. Consequently, as the sample RI varies, the biosensor's transmission spectra shift to different wavelengths. Various samples with different RIs can be analyzed using our biosensor structure. We choose samples whose RI ranges from 1.33 to 1.4, for instance. RIs selected here cover a wide range of samples. First, we determine if there is a shift to higher or lower wavelengths for each RI from the transmission spectrum to characterize the biosensor's sensing abilities. In the next step, we calculate the sensitivity by dividing the wavelength shift by Δn. There are two forms of frequency shift variation by Δn: linear and exponential. A linear fit to the data is applied in order to obtain the slope (S).

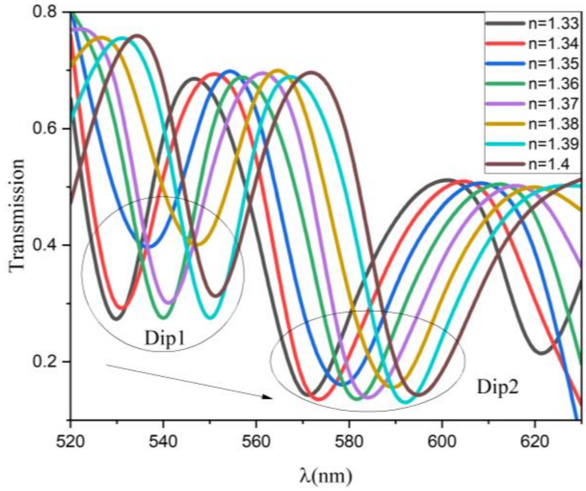

Fig. **2** Transmission spectra of biosensor with silver at waveguide cladding, while the core of waveguide and the resonator are filled with sample. There is a red-shift in the transmission spectra, as shown with the arrow.

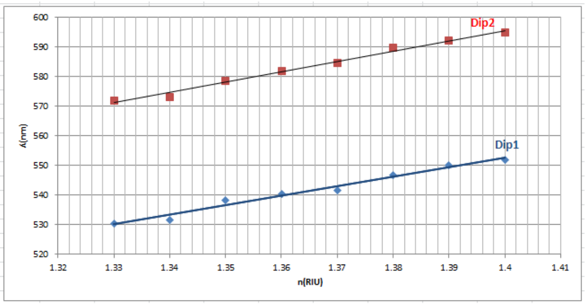

Fig. **3** Sensitivity of the biosensor, by sweeping sample RI's from 1.33 to 1.4.

The transmission spectra of the biosensor have a red-shift by increasing the sample RI from 1.33 to 1.40, as shown in Fig. 2. Figure. 3 shows the wavelength shift in two specified dips (black arrow in Fig.3) of the transmission spectra by varying RIs from 1.33 to 1.39 and by employing a linear fitting. In choosing dips, a clear shift in the transmission spectrum is considered. By applying the linear fitting, the sensitivity of the biosensor for the first dip is 354 nm/RIU and for the second dip is 335.4 nm/RIU, which are high sensitivities.

IV. Conclusion

We design and simulate a biosensor structure based on plasmonic waveguides using asymmetric MZI and a ring resonator. Examples are samples with RIs ranging from 1.33 to 1.4. The sensitivity of the proposed sensor is numerically analyzed by using finite element method (FEM). The positions of the Fano resonance transmission peaks have linear relations with the refractive index of the analyte. With an increase in the refractive index, the Fano resonance peak has a red shift. These biosensors are useful for environmental, chemical, and biochemical monitoring. We can, however, accommodate media having RIs other than those in this specific range. The biosensor's sensing performance embedded in the sample has been tested. Different frequencies can be achieved by changing the sample RI.

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