A Nanoscale Refractive Index Sensor Based on Asymmetric Plasmonic Waveguide With a Ring Resonator: A Review

Shiwei Zou, Faqiang Wang, Ruisheng Liang, Liping Xiao, and Miao Hu

***Abstract*— A novel and simple refractive index sensor based on the asymmetrical coupling of two metal-insulator-metal waveguides with a ring resonator is proposed and investigated numerically by finite-difference time domain. The results show that the resonance wavelengths of the sensor have an approximate linear correlation with the refractive index of the materials under sensing. With optimum design, the value of sensitivity can be achieved as high as 3960 nmRIU^{-1}. The sensor can also be used for other types of sensors, and working for temperature sensing is analyzed as follows. This work is significant for design and application of the sensitive nanometer scale refractive index sensor and temperature sensor.**

***Index Terms*— Surface plasmons, sensors, refractive index, temperature.**

I. Introduction

Surface plasmon polaritons (SPPs) are kinds of electromagnetic waves that propagate along the interface between metal and dielectric. Such waves have an exponential decay to the both sides [1]. Surface plasmons have recently been widely researched in sensing application [2]–[5]. And the propagating surface plasmon polaritons (SPPs) are promising for sensing. SPP sensors have been studied with kinds of ideas such as SPP resonance of nanoparticles [6], and strengthened transmission by nanohole arrays [7]. Due to conquering the conventional diffraction limit, the SPP sensors can be integrated in optical circuits. In the past few years, diverse sensors based on the surface plasmon resonance (SPR) have been investigated [8], [9]. Recently huang et al. reported a high angular sensitivity of over 500 deg.RIU^{-1} [10]. Likewise, refractive index sensing can be achieved for better sensitivity in the case of the Kretschmann configuration, and it is available to fabricate the applied sensors because of its simple structure, the response of sensing can be easily received by theoretically calculating of electromagnetic transmission and reflection at the flat metal film [11]. The plasmonic refractive index sensor with a single defect has been proposed [12]. Another design of plasmonic sensor is based on plasmonic gold mushroom arrays, and the refractive index sensitivity is 1050 nm.RIU^{-1} [13]. Furthermore, the refractive index sensors are suited for manufacturing different kinds of sensors to measure temperature, gas, concentration of chemicals, pressure and bio-sensing [14]–[20]. Besides, the long-range surface-plasmon-polariton (LRSPP) and short-range surface plasmon polariton (SRSPP) waveguide based sensor are meaningful, which could achieve the sensitivity about 10^{-7} RIU and 10^{-6} RIU, respectively [21], [22].

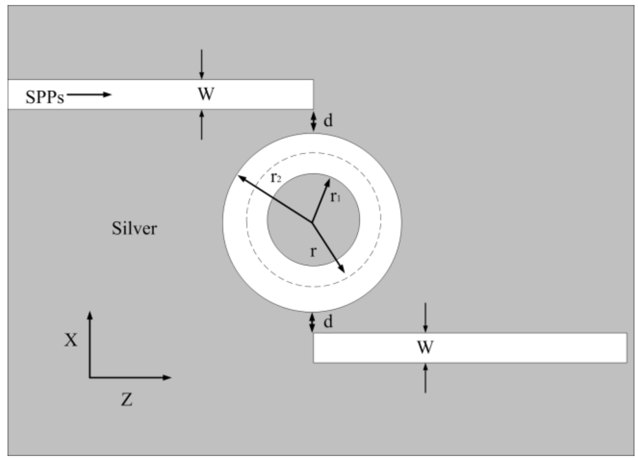

Fig. 1. Structure schematic of two SPPs waveguides with a ring resonator.

In this paper, a nanoscale refractive index sensor based on asymmetric coupling between plasmonic waveguides and a ring resonator is proposed for refractive index and temperature sensing. The sensitivity of our structure is approximately 3.4 times larger than any other reported plasmonic sensor devices [2]–[5], [23]. The sensor performance is simulated by finite- difference time-domain (FDTD).

The structure of paper is as follows. In Section 2, we introduce our structure and theoretical analysis. In Section 3, the simulation results are discussed and the conclusion is in Section 4.

II. The Structure and Theoretical Analysis

The sensor structure is consisted of two slits and a ring resonator, which is shown in Fig.1. The slits and the ring

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resonator will be filled with the material (liquid or gas) under sensing. The widths of the ring and the slits are w, and the inner (outer) radius of the ring is $r_1(r_2)$, $r = (r_1 + r_2)/2$ is the radius of the ring, d is the coupling distance between SPPs waveguide and the ring resonator. In the general cases, d, r and w are set to be 10 nm, 160 nm, and 50 nm, respectively. The surrounding metals are assumed to be silver whose relative permittivity function can be described by Drude model [24]:

$$\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_D^2}{\omega^2 + i\gamma_D\omega} - \sum_{m=1}^{2} \frac{g_{Lm}\omega_{Lm}^2 \Delta\varepsilon}{\omega^2 - \omega_{Lm}^2 + i2\gamma_{Lm}\omega} \tag{1}$$

where ε_∞ is the dielectric permittivity at the infinite frequency and ω is the angular frequency of the incident wavelength, γ_D stands for the frequency of the damped oscillation, and ω_D represents the frequency of the majority of the plasma. These parameters for silver are assumed as follows:

$$\begin{aligned} \varepsilon_\infty &= 2.3646,\ \gamma_D = 0.07489\,ev,\ \omega_D = 8.7377\,ev,\\ \omega_{L1} &= 4.3802\,ev,\ g_{L1} = 0.26663,\ \gamma_{L1} = 0.28\,ev,\\ g_{L2} &= 0.7337,\ \omega_{L2} = 5.183\,ev,\ \Delta\varepsilon = 1.1831,\\ \gamma_{L2} &= 0.5482\,ev\ [25]. \end{aligned}$$

Theoretically, the resonance wavelength of the ring resonator can be obtained by the equation [26]:

$$\frac{J_n'(\mathrm{kr}_2)}{J_n'(\mathrm{kr}_1)} - \frac{N_n'(\mathrm{kr}_2)}{N_n'(\mathrm{kr}_1)} = 0, \tag{2}$$

here $k = \omega\sqrt{\varepsilon_0\varepsilon_r u_0}$, u_0 is the air permeability and ε_r is the frequency-dependent effective relative permittivity. J_n and N_n are the first and second Bessel function with the order n respectively. J_n' and N_n' are derivatives of the Bessel functions to the argument kr. From the equation (2), the resonance wavelength λ_0 can be obtained due to the refractive index of the material and the radius of the ring resonator. Once we select a particular radius, the different resonance wavelength will be observed by the diverse refractive index, by which the device can be used for sensing.

III. Simulation Results and Analysis

A. Numerical Simulation and the Principle of Sensing

The properties of the SPP propagation are simulated by the two-dimensional FDTD method. And the absorbing boundary conditions for all the boundaries are convolutional perfectly matched layers (CPML). In FDTD simulations, the grid sizes are $\Delta x = \Delta z = 5\ nm$ and the time step can be described as $c\Delta t \le 1/\sqrt{(\Delta x)^{-2} + (\Delta z)^{-2}}$, which stem from the Courant condition [27]. As shown in Fig.2, when the refractive index of material is 1 (that means the insulator is air), there are two transmission peaks (with the corresponding value of 64% and 66%) occur at the wavelengths of 850 nm and 1609 nm, corresponding to the first and the second resonance modes of the ring resonator.

Now, we focus on the influence of refractive index n on the peaks of the transmission spectrum. Fig.3 depicts the transmission spectrum of the sensor with the different refractive index n from 1 to 1.4 in steps of 0.05. The other parameters are set as above. When the refractive index is increased, the transmitted peak has a red-shift. The shift of peak II is larger than the peak I due to losses. Furthermore, Fig.4 reveals both the first and second resonance wavelengths have approximately linear relationships with the refractive index of the injected material. According to the linear relation, the refractive index of the material can be easily gained from the resonance wavelength, and the material in turn can be recognized.

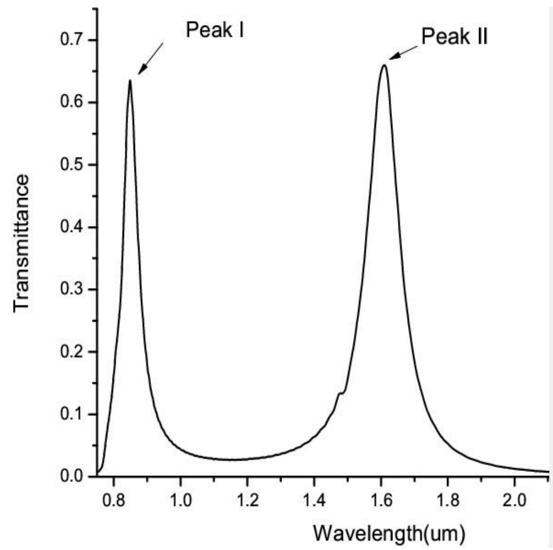

Fig. 2. Spectrum of the transmittance of the structure with refractive index n = 1.

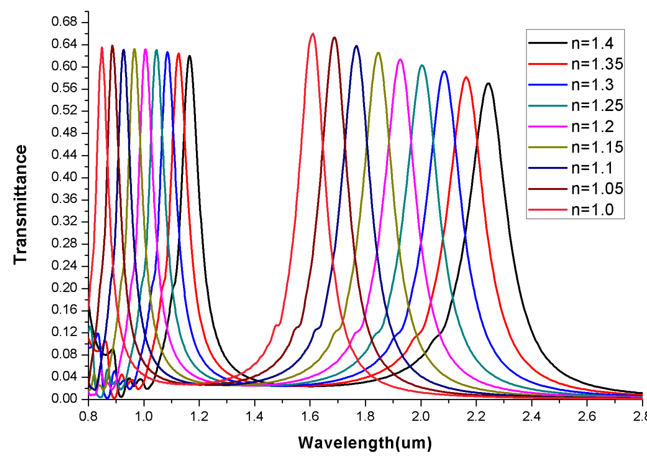

Fig. 3. The transmittance spectra of the structure for different refractive indices of 1-1.4.

B. Results and Discussions

From Fig.3 it can also be seen the shift of the peak I and peak II equals to 314.67 nm and 630.67 nm, respectively. When the refractive index n varying from 1 to 1.4. The sensing sensitivity of refractive index sensor, defined as $d\lambda/dn$, will be 786.67 nm RIU^{-1}, 1576.67 nm RIU^{-1} for the peak I and peak II, respectively. So the peak II is more suitable for sensing though it has a slight lower power transmittance than the peak I. And a high-resolution optical spectrum analyzer can detect it.

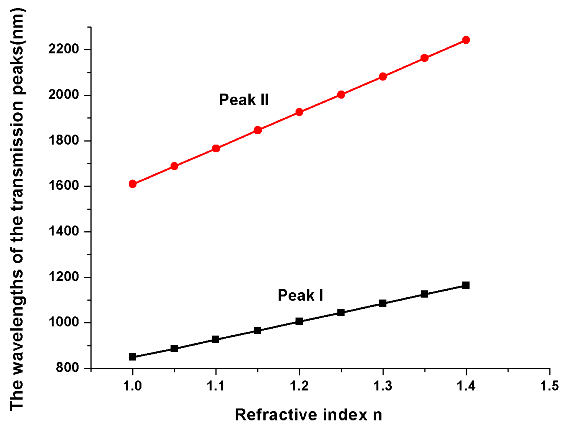

Fig. 4. The two peak wavelengths of the transmission spectrum versus the refractive index n.

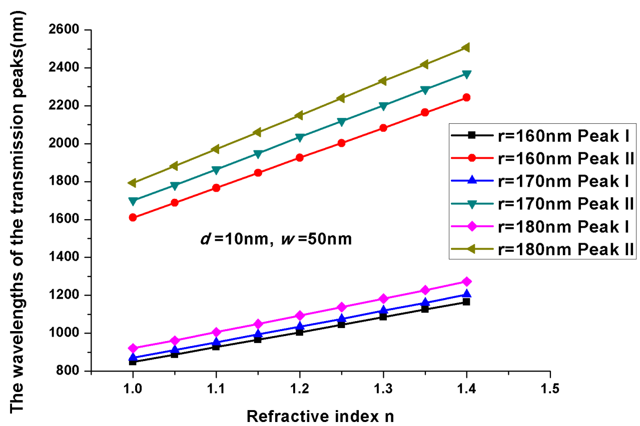

Fig. 5. The peaks of the transmission spectra versus the different refractive index with r = 160 nm, r = 170 nm, r = 180 nm.

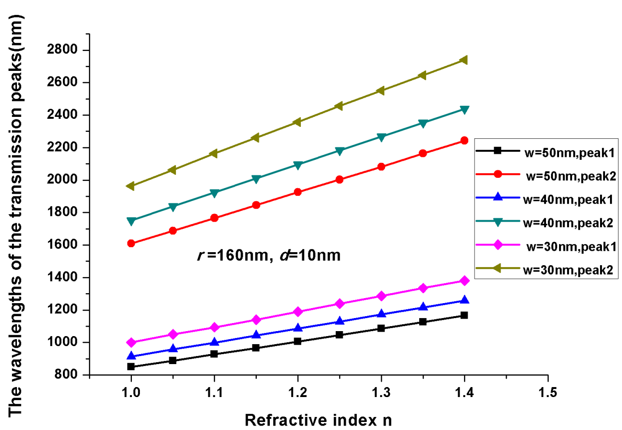

Fig. 6. The peaks of the transmission spectra versus the different refractive index with w = 30 nm, w = 40 nm, w = 50 nm.

Fig.5 illustrates the resonance wavelengths of the sensor as a function of the refractive index of embedded material for different radius of the ring with r=160 nm, 170 nm, 180 nm. Then we calculate the sensitivities corresponding to r=160 nm, 170 nm, 180 nm are 786.67 nm RIU^{-1}, 826 nm RIU^{-1} and 874 nm RIU^{-1} for peak I and 1576.67 nm RIU^{-1}, 1670 nm RIU^{-1}, 1791.67 nm RIU^{-1} for peak II. The results

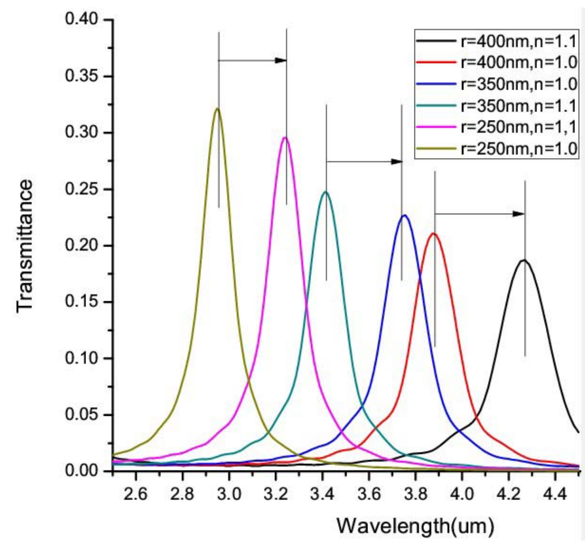

Fig. 7. The transmission spectra for the different radius and refractive index.

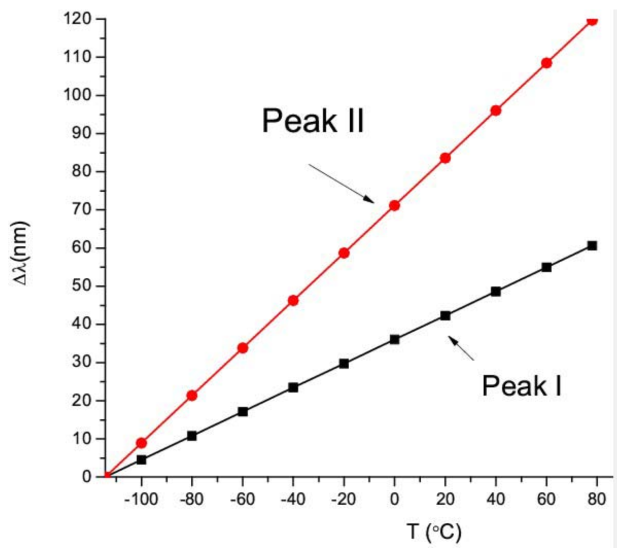

Fig. 8. The shift of the resonance wavelengths versus the temperature.

imply that the sensitivity can be improved by increasing radius of ring. But the transmission loss will be larger with increasing the radius of ring. Fig.6 displays the peaks of the transmission spectra as a function of the refractive index for different widths of the ring and the waveguides with w=30 nm, 40 nm and 50 nm, respectively. Then the sensitivities can be calculated corresponding to w=30 nm, 40 nm, 50 nm are 956.33 nm RIU^{-1}, 860 nm RIU^{-1}, 786.67 nm RIU^{-1} for peak I and 1953.33 nm RIU^{-1}, 1718.33 nm RIU^{-1}, 1576.67 nm RIU^{-1} for peak II. The stimulation results reveal that the sensitivity will be decreased if the widths of the waveguides and the ring are increased.

Fig.7 shows the transmission spectrum of our structure for different refractive index and different radius of ring. The transmission peaks are peak II. d is set to be 10 nm and w is 50 nm. When the refractive index is increased from 1 to 1.1 and the radius of the ring is set to be 400 nm, the shift of the peak II is 396 nm. Therefore, the sensitivity of the refractive index is as high as 3960 nm RIU^{-1}. As far as we know, the sensitivity of this refractive index sensor is 3.4 times higher than other reported refractive index sensors [2]–[5].

C. Temperature and Sensing

One application of the refractive index sensor is the temperature sensing. As for a temperature sensor, we need fill liquid material that must be sensitive to temperature into two slits and the ring. Ethanol is a good choice for high refractive index temperature coefficient 3.94×10^{-4}. The refractive index n related to temperature of ethanol is regarded as

$$n = 1.36048 - 3.94 \times 10^{-4}(\mathrm{T} - \mathrm{T}_0), \tag{3}$$

where the T is the environment temperature, T_0 is the room temperature equals to 20 $°C$. From the Eq. (3), there is the linear relation between the refractive index of ethanol and the temperature of environment. According to the above stimulation, the shift of two transmission spectrum peaks has a linear relation with the refractive index. So the linear relation shown in Fig.8 exists between the shift of two peaks and temperature. When the temperature ranges from -100 $°C$ to 78 $°C$, the shift of peak I and the peak II are 56.11 nm, 110.81 nm respectively. The sensitivity of this temperature sensor can be defined as $d\lambda/dT$. It is obtained 0.31 $nm/°C$, 0.62 $nm/°C$ for the peak I, the peak II, respectively. As the melting point and boiling point of ethanol are -114.3 $°C$, 78 $°C$ correspondingly. This sensor is appropriate for low temperature sensing.

IV. Conclusion

In conclusion, we have proposed an asymmetric SPPs waveguide structure coupled by a ring resonator for the refractive index sensor and temperature sensor. The characteristics of the sensor are analyzed by the FDTD method. It shows that the shifts of the transmission peaks have a linear correlation with the refractive index of the material and the environment temperature. The device is not only simple, but also has a high sensitivity. Furthermore, it has extensive potential application in bio-sensing [20]. The results have a reference for designing the nanoscale high sensitivity sensors.

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