

Design of ultra-sensitive biosensor applying surface plasmon resonance to a triangular resonator

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Abstract: We propose an ultra-sensitive integrated photonic sensor structure using an InP-based triangular resonator, in which a surface plasmon resonance (SPR) gold film is applied on a total internal reflection mirror. We have analyzed and optimized the triangular resonator sensor structure with an extremely small SPR mirror sensing area of $3.3 \times 0.35 \mu\text{m}^2$. Due to the large phase shift in the SPR mirror, a significantly enhanced sensitivity of 930 nm/RIU (refractive index unit) and the maximum peak shift of half free spectral range have been obtained at the SPR angle of 24.125° with Au thickness of 33.4 nm for the change of the refractive index $\Delta n = 1 \times 10^{-3}$. This value is larger than the previous largest value in micro resonator-type biosensors. Moreover, the proposed triangular resonator sensor can be easily made in a micro structure with optical source integration.

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1. Introduction

Biosensor researches using optical properties have been an active research area, as they provide an attractive solution for the accurate and label-free detection of biological interactions. Optical biosensors measure biological interactions using a variation of the optical signal due to the change in absorption or phase within a specific optical wavelength. These biological signals inform the existence of a specific biomolecule and the amount of gen in a medium of interest. Small-sized photonic biosensors have also attracted increasing interest. For example, micro biosensors using a surface plasmon resonance (SPR) waveguide, localized surface plasmon, cantilever, Mach-Zehnder interferometer, and microdisk geometries have been reported [1–6]. The SPR characteristics were first observed optically in the attenuated total reflection (ATR) devised by Kretschmann and Raether [7] and Otto [8]. Ever since the first invention of SPR, it has been widely used in many applications. However, in previous integrated SPR sensors, external optical components for light source and optical signal detection had to be used. On the other hand, owing to its very high Q-factor resonances and steep slopes, photonic micro-ring resonators have been recently employed in biological and chemical sensing [9–11]. Sensitivities of 26 nm/RIU (refractive index unit), 140 nm/RIU, 30 nm/RIU, 390 nm/RIU, 600 nm/RIU, and 800 nm/RIU have been reported for photonic biosensors utilizing microspheres [12], planar rings [9], liquid core optical ring resonators [13], micro capillary resonators [14], prism coupled micro-tube resonators [15], and liquid ring resonator optical sensors [16], respectively. Though there have been continuous efforts to reduce the size of these ring-type resonators, the diameter of micro-ring resonators cannot be reduced indefinitely due to the increase of radiation loss. Therefore, we have studied an angled resonator based on total internal reflection (TIR) mirrors in order to minimize the radiation and propagation loss caused by the bended side wall [17]. Very compact cavities can be formed by combining TIR mirrors with regular waveguides. We have also demonstrated the InP-based triangular resonator with TIR mirrors having a high on-off ratio in prior work [18]. Figure 1 depicts the top schematic of the proposed sensor structure with MMI, TIR and SPR mirrors. The resonator consists of two TIR mirrors and an SPR mirror with a sharp incident angle for the resonance. The triangular resonator is integrated with a semiconductor optical amplifier (SOA) structure for a broadband light source. Previously, we have experimentally confirmed that the optical gain of the integrated SOA can demonstrate a flat optical profile over 40 nm at wavelengths from 1540 to 1580 nm [19]. The widths of waveguide and the MMI are chosen to be 3 and 9 μm , respectively. The proposed sensor has an extremely small sensing area of $3.3 \times 0.35 \mu\text{m}^2$ on the SPR mirror.

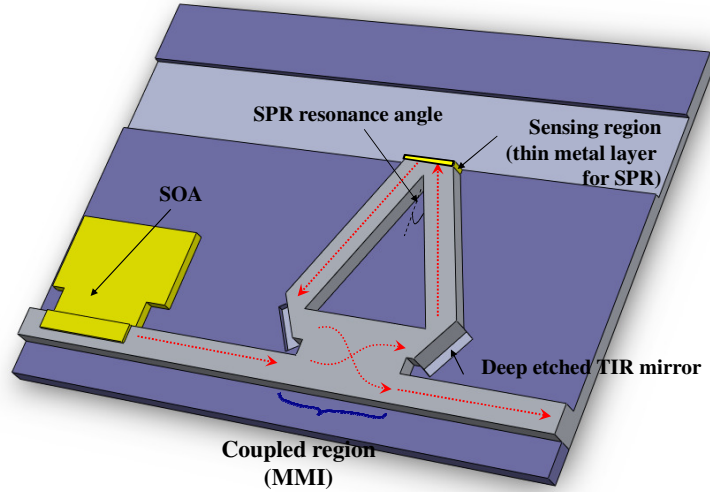


Fig. 1. Top-view schematic MMI-coupled triangular resonator with SPR and TIR mirrors.

As shown in Fig. 1, one of the TIR mirrors can be used as a sensing region after applying SPR, which works similarly to an ATR having the drastic phase transition at the resonance angle [20]. Since the SPR mirror is embedded in a resonator structure, the phase change of the SPR can be accumulated resulting in a huge peak shift regarding the resonance peak. Therefore, it is believed that this configuration provides good advantages by increasing the sensitivity of the biosensor even with the extremely small sensing area of the SPR mirror and in integrating the optical source such as the SOA for a micro structure sensor. Moreover, these devices can easily be integrated with light sources, detectors, modulators, and other passive components, giving rise to the possibility of micro resonator-type full photonic integrated biosensor structures. These are typically achieved by a deep etching mirror to provide a non-circular configuration in order to reduce propagation and excessive radiation loss. The material itself and fabrication process of the proposed configuration are fully compatible with those of the conventional laser diode.

In this paper, we design a triangular ring resonator with TIR and SPR mirrors to achieve compactness as well as high sensitivity. Here, the optimum gold thickness for the SPR mirror, the resonance angle, and the multimode-interference (MMI) length are calculated. The following sections describe the theoretical analysis of the SPR in the triangular ring resonator. This is followed by optimized results and discussions. Finally conclusions are given.

2. Theoretical analysis

2.1 The resonator model

We can simplify the analysis of the triangular resonator by using a transfer function of the single-ring resonator as shown in Fig. 2. Using this model, the relationship in the directional coupler region can be represented by

$$\begin{bmatrix} E_{t1} \\ E_{t2} \end{bmatrix} = \begin{bmatrix} t & \kappa \\ -\kappa^* & t^* \end{bmatrix} \begin{bmatrix} E_{i1} \\ E_{i2} \end{bmatrix}, \quad (1)$$

where κ and t are the coupling and the transmission coefficients, respectively. The transfer function for the round trip in the ring is given by

$$E_{i2} = \alpha \cdot e^{j\theta} E_{t2}, \quad (2)$$

Here, the total phase difference per round trip $\theta = \theta_{ring} + 2\theta_{TIR} + \theta_{SPR}$, where θ_{ring} is the phase change per round trip, θ_{TIR} is the phase shift by the TIR mirror, and θ_{SPR} is the phase shift by the SPR mirror. α is the attenuation coefficient given by $\alpha = \exp(-a_{linear} \times L - a_{total\ mirror\ loss})$ including the optical propagation loss and the scattering loss of the TIR and SPR mirrors. Here, L is the total resonator length. Then, the transmitted intensity can then be expressed as

$$P_{t1} = |E_{t1}|^2 = \frac{\alpha^2 + |t|^2 - 2\alpha|t|\cos\theta}{1 + \alpha^2|t|^2 - 2\alpha|t|\cos\theta}. \quad (3)$$

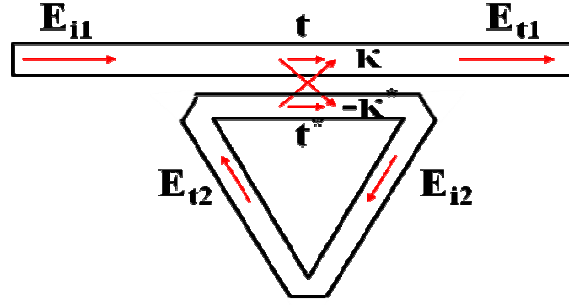


Fig. 2. Triangular resonator schemes used for the theoretical analysis.

Since the Q-factor is directly affected by the optical loss of the ring resonator, steep slopes of the resonance are obtained in the ring resonator with low loss. Therefore, the TIR mirrors with low loss are important to fabricate the triangular resonator with high Q-factor and steep slope.

2.2 The optical properties of the structure

In regards to the design of ultra-sensitive biosensors, we need to make a thorough investigation and analysis of the optical properties of the structure. The critical angle for the water (refractive index: 1.311) interface mirror is 23.89° in the InP-based triangular resonator. For the application of SPR on a mirror facet, the angle needs to be larger than the critical angle of the TIR.

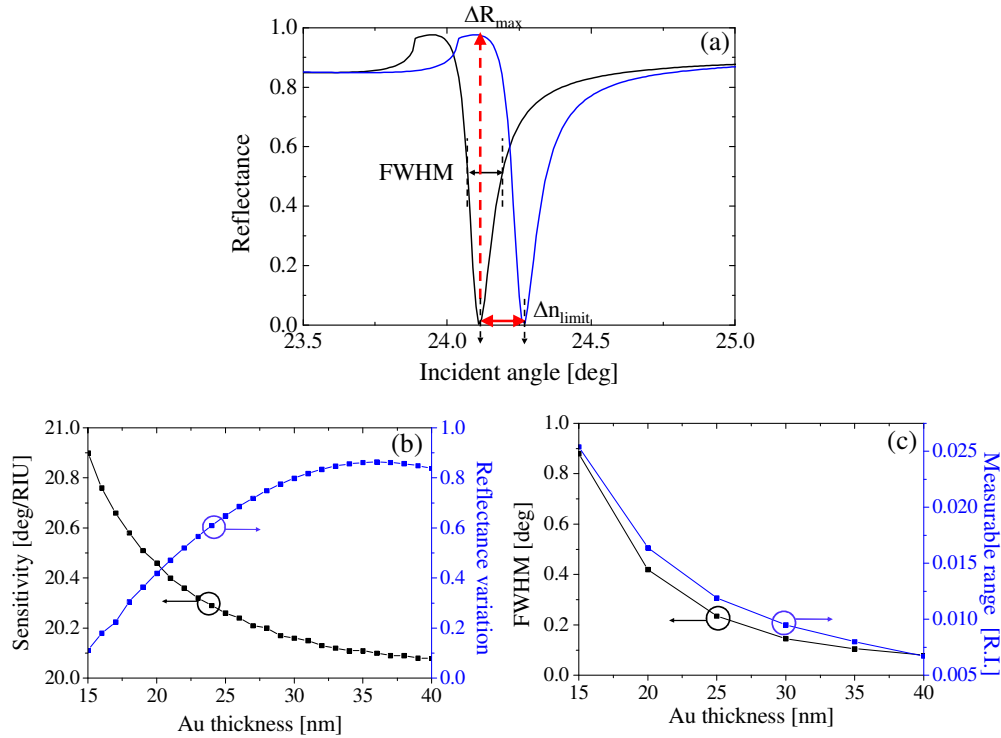


Fig. 3. (a) Variation of reflectance according to the SPR angle change due to the refractive index increment of 0.0077 on the metal layer, (b) reflectance variation and sensitivity as a function of Au thickness for changing the refractive index of 0.1, (c) full width half maximum of the resonance peak and the measurable sensing range as a function of Au thickness.

The maximum measurable reflectance change ($\Delta R_{\max}$) of the SPR due to the refractive index variation of 0.0077 on the metal layer is shown in Fig. 3(a). Sensing parameters such as the power variation, the full width half maximum (FWHM), and the maximum measurable refractive index range (Δn_{limit}) corresponding to $\Delta R_{\max}$ at a fixed resonance angle are shown in Fig. 3(a). Figure 3(b) demonstrates the reflectance variation and the sensitivity as a function of Au thickness in the SPR mirror interface. At the resonance angle, the sensitivity decreases from 20.9 to 20.1 deg/RIU as the Au film thickness increases from 15 to 40 nm. However, the reflectance variation increases up to 0.86 for the 35 nm Au thickness. Figure 3(c) shows the FWHM of the resonance peak and the sensing detection range for the refractive index variation. As shown, both the measurable range of Δn_{limit} and the FWHM are decreased according to the increase of the Au thickness.

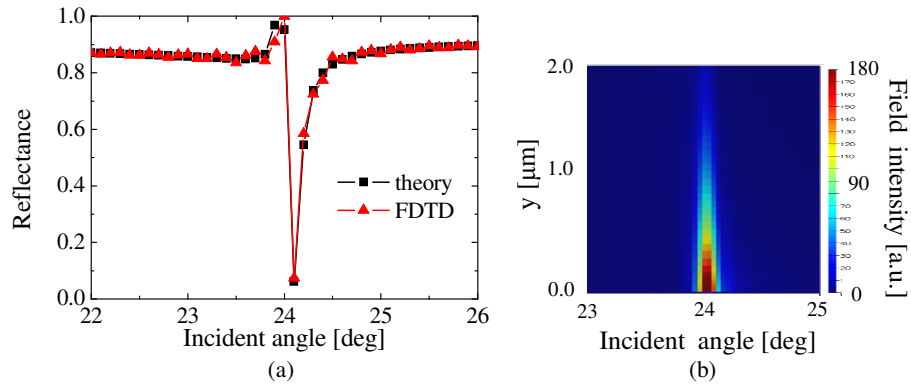


Fig. 4. (a) SPR characteristics obtained by the theory and the FDTD method, (b) evanescent field intensity as a function of incident angle at 35 nm Au thickness.

Figure 4(a) shows the incident angle-dependent reflectance change at the SPR mirror with a water interface. Here, the SPR angle of 24.125° is obtained both by the theory and the FDTD plane wave analysis. Both results indicate a perfect agreement indicating the validity of our theoretical approach. We used the effective refractive index of 3.2374 for the mirror block and gold film thickness of 35 nm. The complex permittivity of the gold film is $\epsilon_m = -131.95 + j12.65$. Figure 4(b) shows the evanescent field intensity along the y-direction as a function of the incident angle. The maximum evanescent field is shown at the resonance angle of 24.125° as expected. Easy integration of the triangular surface plasmon resonator can be achieved by using a MMI coupler as shown in Fig. 1. In the MMI design, we have chosen an extremely small MMI coupler, which couples the output power by mode interference into the triangular surface plasmon resonator. The MMI length was determined to be $100\ \mu\text{m}$ based on our FDTD simulation result. Approximately 3 dB of the incoming power is coupled into the resonator per pass.

3. Results

Figure 5 shows the resonance peak shift of the triangular resonator as a function of the incident angle for the SPR mirror. Here, the refractive index change of the SPR mirror interface is set to be $\Delta n = 1 \times 10^{-3}$. The maximum resonance peak shift is shown at the SPR angle of 24.125° .

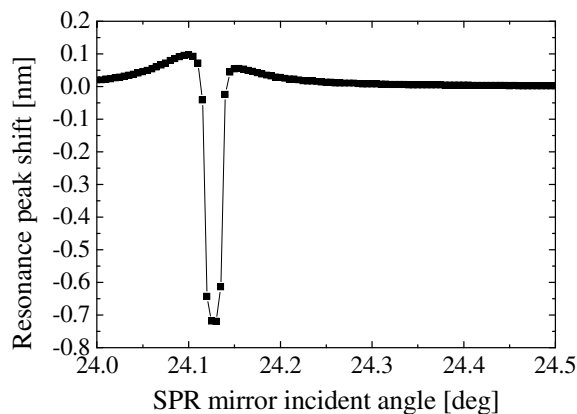


Fig. 5. Resonance peak shift of the triangular resonator as a function of the incident angle of the SPR mirror for $\Delta n = 1 \times 10^{-3}$.

Figure 6 shows the simulation results of the triangular surface plasmon resonator by the FDTD method. Here, the FDTD analysis is developed with the full structure of the triangular ring resonator. The total length of the triangular resonator used in the FDTD calculation is 398 μm . The incident angles of the TIR and the SPR mirrors are fixed at 32.94° and 24.125° , respectively. Using the FDTD Gaussian wave method, for a more realistic simulation, the TIR mirror loss of 0.86 dB/facet and the SPR mirror loss of 3.03 dB/facet are obtained.

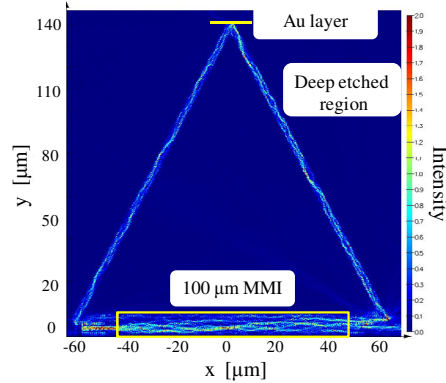


Fig. 6. FDTD simulation result of the triangular surface plasmon resonator.

The Q-factor of 1860 is also obtained in the triangular ring resonator with these mirror structures. In our proposed structure, the whole structure of the triangular resonator is assumed to be deeply etched for easy fabrication. The most important aspect regarding biosensor performance is determined by the wavelength sensitivity per a unit refractive index change and the Q-factor. Here, the obtained mirror loss and the Q-factor results from the FDTD simulation are applied to the theoretical resonator calculation.

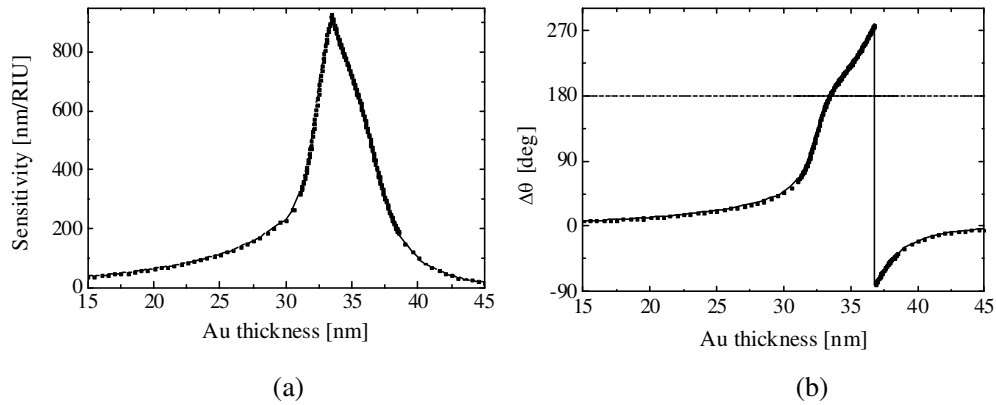


Fig. 7. (a) Sensitivity of the triangular resonator as a function of Au thickness, (b) θ_{SPR} difference for $\Delta n = 1 \times 10^{-3}$ at SPR mirror.

Figure 7 shows the triangular sensor sensitivity and the difference of θ_{SPR} for the change of the refractive index $\Delta n = 1 \times 10^{-3}$ as a function of Au thickness. θ_{ring} and θ_{TIR} are constants because these values are determined by the ring resonator path and the refractive index on the mirror boundary, respectively. However, θ_{SPR} have a drastic phase shift for the change refractive index on the SPR mirror. When the θ difference is 180 degree, the sensitivity is maximized as shown in Fig. 7. In the resonator-type sensor structures, the maximum wavelength shift of the resonance peak would be the half of the free spectral range (FSR). In our proposed sensor, the maximum peak shift of 0.5 FSR and the sensitivity of 930 nm/RIU

have been obtained at the SPR angle of 24.125° with Au thickness of 33.4 nm for the change of the refractive index $\Delta n = 1 \times 10^{-3}$.

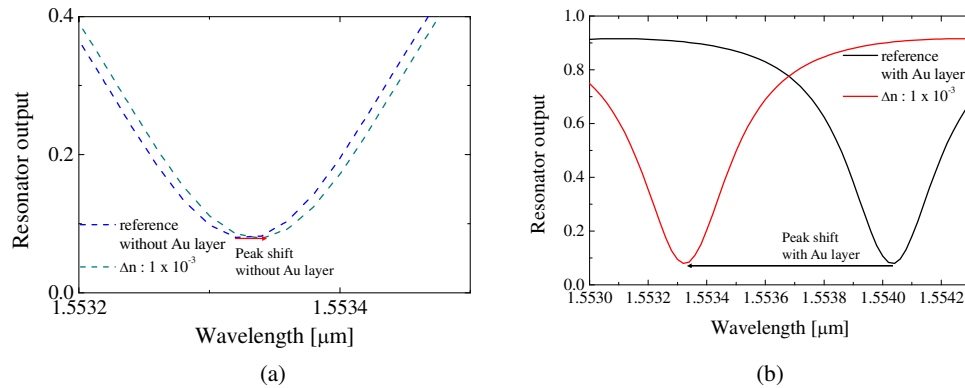


Fig. 8. (a) Reflectance of the triangular resonator without the Au film on the SPR mirror, (b) reflectance of the triangular resonator with 35 nm of the Au film on the SPR mirror.

The peak shift for the triangular resonator without/with the Au film on the SPR mirror are 0.02 nm and 9.30 nm for $\Delta n = 1 \times 10^{-3}$ as shown in Fig. 8, respectively. The triangular resonator with the Au film on the TIR mirror, i.e. with a SPR mirror, has a drastic resonance peak shift with respect to the wavelength. The sensitivity of the triangular resonator sensor without the Au film on the TIR mirror is even lower than that of the conventional ring resonator sensor due to the small sensing region of the TIR mirror. However, the triangular resonator sensor with a SPR mirror has a high sensitivity at the SPR angle. The enhanced sensitivity comes from the fact that the phase change of SPR results in a huge peak shift regarding the resonance peak. As a result, we have obtained that the sensitivity of the triangular surface plasmon resonator is larger than the largest previous value in micro-resonator type biosensors.

4. Conclusions

We have optimized a triangular surface plasmon resonator sensor to achieve compactness and high sensitivity for ultra-sensitive biosensor. By using the FDTD analysis, we have obtained the SPR characteristics, the mirror losses, and the power loss, and applied them to the theoretical resonator calculation. This configuration provides good advantages to increase the sensitivity in the extremely small sensing area of the SPR mirror and to integrate the optical source for a micro structure sensor. The properties such as the optimum gold thickness in the SPR mirror, resonance angle, and the Q-factor of our proposed sensors are calculated. When the gold thickness in the SPR mirror is 35 nm, the Q-factor and the resonance angle are 1860 and 24.125° , respectively. Although the Q-factor is smaller than the previous results, the enhanced sensitivity of 930 nm/RIU, which is larger than the largest previous value in micro resonator-type biosensors, has been obtained at the resonance angle of 24.125° . In addition, it is believed that the proposed triangular resonator sensor can be easily made in an integrated structure with other optical components.

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