A compact-size and ultrasensitive optical biosensor using a double-spiral microresonator

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Abstract—**A structure of a double-spiral microresonator is demonstrated for high-sensitive biosensing of a microliter sample volume of biomolecules. The microring resonator has been applied as a highly potential label-free biosensor; however, the sensitivity still needs to be improved due to the restriction of the sensing surface. In this report, a resonator with two Si-based spiral waveguides connected by an S-shaped channel is designed to be positioned in a hundred-micrometer-width fluidic channel. The enhanced sensing surface on the same footprint of the double spiral resonator contributes a high bulk sensitivity of about 1,500 nm/RIU, 10-fold more sensitive than the sensitivity of the microring resonators according to 2D-FDTD simulation results. In addition, the fabricated double spiral resonator shows Q-factors of 14,000 in air and 12,000 in water, which doubles that of the conventional microring. The double-spiral structured microresonator can be further applied with a microfluidic channel for detecting changes in biomolecules in real time.**

Keywords— Double-spiral; microresonator; sensing surface

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I. INTRODUCTION

Silicon photonic has gained significant attention in the application of label-free biosensing by utilizing the effect evanescent field surrounding the sensing surface to detect different target biomolecules of DNA, antibodies, and antigens. Compared with the FET biosensor, the photonic biosensor can cover the problem of charge-screening in high ionic solution [1–4]. Besides, the current photonic integrated technology enables the ease of fabrication and mass production. There are several promising candidates for photonic devices, such as silicon microring resonators, photonic crystals, Mach-Zehnder interferometers, and fiber-photonic sensors [2–5]. Among these types, the SOI microring resonator, which can recognize the attached biomolecules as the changes of refractive indices of the waveguides, expresses higher impacts because of the simple structure, fast response, reusable device, and multiplexed biomolecular analysis [6, 7]. Nevertheless, sensitivity is still a research issue for detecting small refractive index changes. The sensitivity of the microring resonator depends on the contact between the electrical field of the waveguide surface and the target biomolecules [8–10]. The more contact surface becomes, the higher the sensitivity becomes. However, in a conventional structure of the microring resonator, the contact surface of microring is mainly on the top of the waveguide, and a large number of biomolecules near the microring on the same footprint will be missed for the biosensing. Hence, most biomolecules must be attached to the waveguides to have a high sensitivity. Although a large microring resonator might be chosen for the application of biosensing, the footprint of the optical resonator becomes larger, which can limit the possibility of using a narrow microchannel for the small-volume measurement [11].

In this report, we propose a design of Si resonator structure that effectively uses the sensing footprint to obtain a higher sensitivity for detecting small amounts of solution. In the silicon-based microring resonator biosensor, the waveguide surface is also the sensing surface, where the biomolecules contact the electrical field surrounding the waveguide. Even the microring has a micrometer-order surface size, but the ring width limits the sensing surface to about a submicron. Based on the principle mentioned above, we designed a double-spiral structure to increase the sensing area in a small footprint to improve the sensitivity of the biosensor. We utilized 2D Finite-Difference Time-Domain (FDTD) method to simulate the output spectrum and calculate the sensitivity. The characteristics of the fabricated double-spiral resonator are also discussed.

II. BIOSENSING PRINCIPLES AND DESIGN OF DOUBLE SPIRAL RESONATOR

A. *Sensitivity and quality factor*

Silicon microring resonator is formed on a SOI substrate. Due to the refractive index contrast between a core layer of Si (n = 3.45) and cladding layers of SiO2 or air, liquid (n = 1 to 1.56), strong confinement is formed within the waveguides. The biosensing mechanism is that the evanescent field changes with the changes in the refractive index of the target biomolecules attached to the waveguide surface, causing the resonance change in the resonance wavelength. Here, three factors affect the sensing ability: bulk sensitivity, surface sensitivity, and quality factor (Q factor). The bulk sensitivity (S) is defined as a resonance wavelength per a unit of refractive index (nm/RI), which is given by

$$S = \frac{\Delta\lambda}{\Delta n} = \frac{1}{\Delta n} \times \frac{\Delta n_{\mathrm{eff}}\lambda_0}{n_{\mathrm{g}}} \qquad (1.)$$

Here, the $\Delta\lambda$ is the shift of the wavelength, and the Δn is the refractive index change of the cladding layer o r the

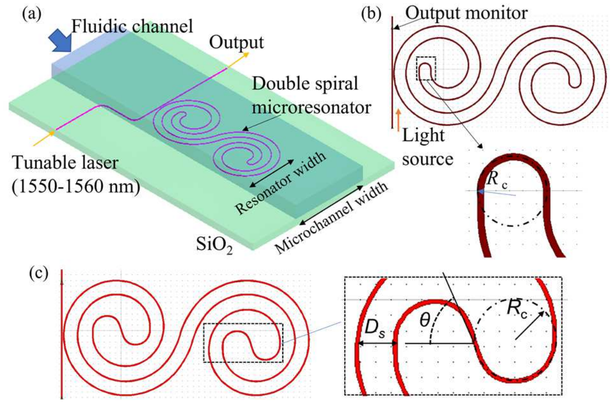

Fig. 1. (a) Schematic of double spiral structured microresonator. (b) Design of double-spiral microresonator using 2D FDTD simulation. (c) Design of DSS microresonator to reduce optical loss in the curving region.

binding analyte, Δn_{eff} is the change of effective refractive index and n_{g} is the group index. The more significant the wavelength shift is, the higher the biosensor sensitivity.

Surface sensitivity expresses the resonance wavelength shift per unit of the thickness of the attached target biomolecules (pm/nm). Here, the refractive index of the attached biomolecules will be fixed while the thickness will change. When the exponential decay of the evanescent field over the waveguide surface, the surface sensitivity is an essential value for detecting target biomolecules.

The Q factor of the resonator is also a sustainable factor for high sensitivity. The formula of Q is as follows:

$$Q = \frac{\lambda}{\mathrm{FWHM}} \cong \frac{n_{eff}L}{\lambda}F \qquad (2.)$$

Here, the FWHM is the full-width-at-half-maximum of resonance wavelength, and F is the fineness. When the Q factor gets high, it becomes accurate to observe a small shift of the resonance peak. It is possible to increase the Q factor by increasing the resonance circumference.

B. Design of the double spiral resonator

The schematic diagram of a photonic biosensor using the double-spiral resonator is shown in Fig. 1(a). The proposed structure aims to enhance the sensing surface in a small resonator footprint to detect a small solution by designing a spiral-shaped waveguide and an S-shape channel. The spiral resonator makes the width of the microchannel smaller, and the volume of the target solution can be reduced. Here, the width of the resonator should be fixed at about 40 µm, which is an ideal width for the alignment with a PDMS-microchannel for detecting several-µL solutions. The S-shape channel for connecting two spirals can increase the waveguide surface and maintain the minimized width of the cavity.

TABLE I. OPTICAL POWER LOSS AND SENSING SURFACE WHEN CURVATURE RADIUS CHANGES.

R_c (µm)	1	2.5	3
Power loss (%)	14	5.5	5
Sensing Surface (µm^2)	1728	1188	998

TABLE II. OPTICAL POWER LOSS AND Q FACTOR WITH A DIFFERENT TYPE OF RESONATOR.

	20-µm microring	Resonator A R_c=D_s=2.5 µm	Resonator B R_c= 5 µm; D_s= 2.5 µm		
Angle(°)	N/A	N/A	72	70	63
Power loss (%)	N/A	5.5	0.8	1.4	1.6
Q factor	8000	15000	19000	18000	17800

Based on these approaches, we designed spiral rings roughly by using Python. To optimize the parameters of the double spiral, we simulated the optical loss and Q factor by employing the simulation of 2D-FDTD from Synopsys. A model of the double spiral microresonator is shown in Fig. 1(b). A TM-mode impulse light from a bus waveguide will be coupled with the microresonator, resulting in the transmission light spectrum in the output. The gap between the bus waveguide and the resonator is 200 nm. To reduce the optical loss from the curves, we modified the radius of the inner curvature near the center of each spiral (R_c). The value of R_c is changed to satisfy a structure taking the balance of the large waveguide surface and the small optical loss caused by the arc. Besides, the space between two adjacent waveguides of the resonator (D_s) will be as wide as R_c. Table I shows the simulated optical power loss and the waveguide surface when the radius at the inner curvature was changed from 1 µm to 3 µm. In this simulation, the width and height of the waveguide are 500 nm and 240 nm, respectively. The refractive index of the Si resonator was 3.45, and the refractive index of the cladding layer was 1.45. A value of the effective refractive index was calculated based on the structure of the waveguide for the simulations in 2D-FDTD. Accordingly, the curvature radius of 2.5 µm was selected to balance a small optical loss and a large waveguide surface. In summary, the resonator was designed with a footprint size of the width of 41 µm and length of 88 µm, having a sensing surface of 189 µm^2, which the footprint size was reduced by 680 times compared with the microring resonator. We named this structure resonator A.

To eliminate the optical loss, the design of the curvature was studied. Fig. 1(c) shows a resonator model with an R_c value larger than D_s. We named this type of structure resonator B. The impact point of the structure of resonator B is the effect of the angle of the connection waveguide between two arcs on the optical loss. Table II shows the results of optical loss when the angle (θ) changed and the Q factors of each structure. The power loss when θ is 72° becomes lower than 1%, better than the resonator A. In addition, Table II also lists the Q factors of double spiral designs. Q factors of the double spiral structure are higher than that of the microring resonator, having a radius of 20 µm with a factor of 2. Significantly, the resonator B with θ of 72° can become 19,000. Hence, it is possible to reduce the power loss by a design of curving the waveguide through the center of the spiral with enlarged R_c.

III. RESULTS

A. Simulation results of sensitivities

In this part, we report the resonator A model for the sensitivity simulation and properties of the fabricated device.

The bulk sensitivity of the double spiral resonance was investigated using the FTTD method. The waveguide model consists of a Si waveguide, 10-nm-thick SiO_2, and a 10-nm-thick biomolecule layer with different refractive indices from 1.45 to 1.455. To reduce the simulation time, the effective refractive index of the waveguide for different attached biomolecular layers was calculated using Finite Element Method (FEM) in the 2D-FDTD. We observed the transmission spectra for the input light in TM mode. The resonance wavelength shifted as a function of the different refractive indices. As a result, the bulk sensitivity of the double spiral resonator was 1,500 nm/RIU, while the bulk resistivity of the 20-µm-radius microring resonator was 120 nm/RIU. This result indicates that the double spiral resonator could increase bulk sensitivity by ten without increasing the resonator footprint. Here, we noticed another advantage of the double spiral design: due to the small footprint of the double spiral, the simulation time could be decreased over ten times compared to the microring having the same circumference.

Furthermore, the surface sensitivity was also calculated. For sensing biomolecules, a model of layers stacked onto the Si waveguide includes 10-nm-thick SiO_2, 1.5-nm-thick Aminopropyltriethoxysilane (APTES) and glutaraldehyde, and a protein layer with different thicknesses. Here, APTES+glutaraldehyde has an RI of 1.46 [12]. A protein layer has a standard RI of 1.53 [13]. The resonance wavelength shifted as the thickness of the protein layer changed from 1 nm to 5 nm. As a result, the surface sensitivity of the double spiral resonator and 20-µm-radius microring resonator was 4,500 pm/nm and 500 pm/nm. The improvement of surface sensitivity results when the biomolecule-contacting surface of the top surface and side surface of the waveguide increases.

B. Characteristics of the fabricated resonator

The double spiral resonator was formed on an SOI substrate with a 250-nm-thick top Si layer and 2.5-µm-thick BOX layer. Based on the design of Resonator A, the device was fabricated by microfabrication processes with electron beam lithography (EBL), a reactive-ion-etching etching (RIE), and plasma surface treatment [14]. Fig. 3 shows the SEM images of the fabricated double spiral resonator. The gap between the bus waveguide and resonator was 200 nm, and the waveguide width was 490 nm. The radius R_c was 2.5 µm. This device was used for the evaluation of optical characteristics. Edge couplers were utilized for coupling

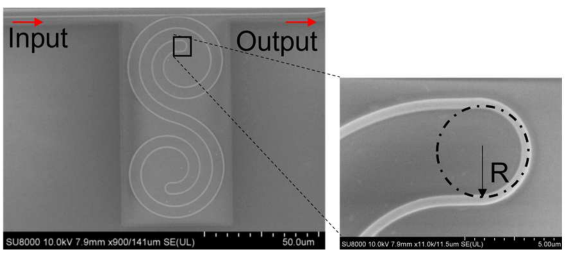

Fig. 2. SEM images of double-spiral ring resonator with curvature radius of 2.5 µm

light to the bus waveguide. The size of the device was a width of 8 mm and a length of 20 mm. Besides, the conventional

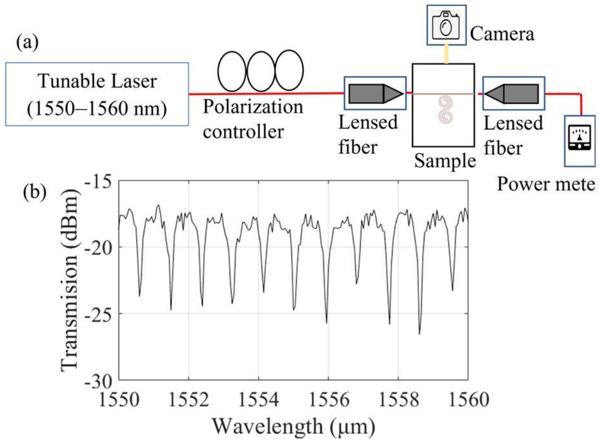

Fig. 3. (a) Schematic diagram of measuring instrument used for evaluation of optical characteristics. (b) Transmission spectrum of the fabricated double-spiral resonator in air

20-µm-microring resonator was fabricated for the characteristic comparison.

A schematic of the setup for measuring the transmission spectra is shown in Fig. 3. The CW light with a wavelength from 1,550 to 1,560 nm was generated by a tunable laser and followed by a polarization controller for optimizing the light mode, then coupled to the Si waveguide by a lensed fiber. The output light was detected by an optical power meter, and the power was collected in real time by LabVIEW. Fig.3 (b) shows the transmission spectrum for the double spiral resonator in the air. From this result, the FSR was 0.9 nm to 1.2 nm, as much as the simulation result. The Q factors in the air and in water were 14,000 and 12,000 at wavelengths close to 1,555 nm, respectively. The Q factor of 20-µm-radius microring resonator was about 7,000. As a result, the double spiral expresses a better optical characteristic than the conventional microring resonator. This structure can contribute to an ultrasensitive sensor of biomolecules. T The optical characteristics of B resonator structures and microchannel for a small amount of solution are now investigated.

IV. CONCLUSIONS

We have proposed a novel design of a double spiral microresonator that can enlarge the waveguide surface in the resonator footprint of 41 µm × 88 µm, 680 times smaller than the microring resonator having a save sensing surface. The improvement of the sensitivity and characteristics of the double spiral has been investigated in the simulated 2D-FDTD calculation and the fabricated device. The fabrication optimization and the measurement in solution with different concentrations combined with the microfluidic are now studied for further application of detection of biomolecules.

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