Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp133-134

C-1-06

Highly-Sensitive Optical Biosensor Based on Si Microring Resonator-Loaded Mach-Zehnder Interferometer

Soichiro Yoshida, Shintaro Ishihara, Taro Arakawa and Yasuo Kokubun

Graduate School of Engineering, Yokohama National University
79-5 Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa 240-8501, Japan
Phone: +81-45-339-4143 E-mail: arakawa@ynu.ac.jp

Abstract

Highly-sensitive optical biosensor based on a silicon microring resonator-loaded Mach-Zehnder interferometer (MRR-MZI) is demonstrated. Avidin solution with the concentration as low as 20 pM is successfully sensed by the MRR-MZI.

1. Introduction

Optical biosensors have attracted much attention for detecting biomarkers, such as proteins. Compactness, cost reduction, reducing detection time, and high sensitivity are demanded in these sensors. Although surface plasmon resonance (SRP) sensors [1] have been put to practical use as high sensitivity optical biosensors, their size is large and their measurement system is complicated. Therefore various kinds of compact optical biosensors based on waveguide structures, such as slot waveguides [2], photonic crystals [3,4], directional couplers [5]. In addition, silicon microring resonator (MRR) biosensors fabricated using silicon CMOS process has been proposed that meets the above requirements [6,7].

In this study, we demonstrate a novel biosensor based on a silicon MRR-loaded Mach-Zehnder interferometer (MRR-MZI), and discuss its sensing characteristics experimentally, using ethanol solutions with various concentrations and avidin solutions of 20 pM. High-sensitivity optical biosensor is expected to be realized by using the combination of the MZI and the effect of the phase change enhancement in the MRR.

2. Structure of MRR-MZI Biosensor

The schematic top and cross-sectional views of the proposed silicon MRR-MZI sensor are shown in Figs. 1(a) and (b), respectively. It is composed of an MZI with a single MRR in one arm. The waveguide has a 210 nm-thick and 400 nm-wide Si core surrounded by a 2-μm-thick SiO_2 cladding layer. The 1×2 multimode interference (MMI) couplers are used in the MZI for input and output ports.

The MRR is a sensing section and its upper SiO_2 cladding layer is removed. The change in concentration of solutions or proteins contacting with a surface of the Si MRR waveguide is detected as a change in environmental refractive index of the MRR region. The change in the environmental refractive index causes the change in phase in the MRR, leading to the steep change in the intensity of the output light of the MZI.

Fig. 2 shows a schematic top view of an MRR with a busline waveguide (inset), and the effective phase shift ϕ_{eff} (the phase of the optical electric field transmitted from Ports 1 to 3) vs the single-pass phase shift ϕ for various κ, assuming the round-trip length of 69.3 μm and propagation loss of 1.3 dB/mm.

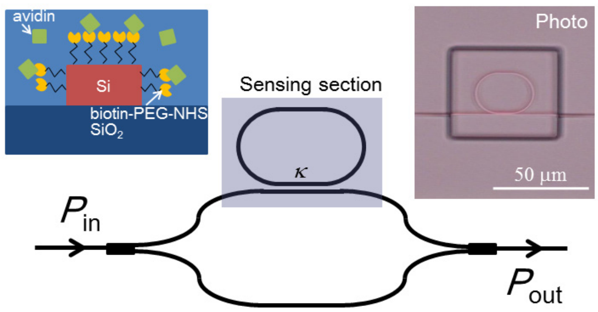

Fig. 1. Schematic view of proposed and fabricated silicon MRR-MZI biosensor, and cross-sectional view of Si waveguide at sensing section (Inset). Avidins are fixed on surface of Si waveguide through biotin-PEG-NHS (see Sec.3).

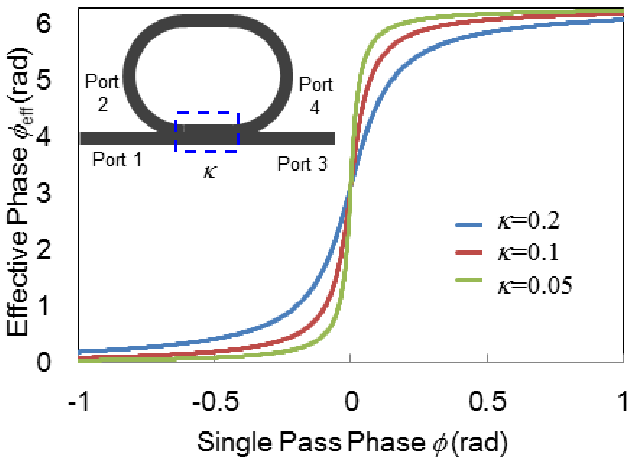

Fig. 2. Schematic top view of MRR with busline waveguide (inset) and calculated effective phase ϕ_{eff} vs single pass phase ϕ in MRR arm.

In the vicinity of $\phi = 0$, that is, in the on-resonance state, the marked nonlinearity and the single-pass phase shift are strongly enhanced. Using the combination of the MZI and the effect of the phase change enhancement in the MRR [8], a compact and highly-sensitive sensor for the environmental refractive index change can be realized. The sensitivity of the proposed sensor mainly depends on the coupling efficiency κ between the MRR and the arm waveguide of the MZI. The designed round-trip length and coupling efficiency κ of the

MRR are 69.3 μm and 0.2, respectively. The quality (Q) factor of the MRR is calculated to be 4.72×10^3. The devices were fabricated on an SOI substrate using CMOS compatible process.

3. Sensing Characteristics

As a preliminary experiment, the sensing characteristics of the MRR-MZI sensor were investigated using ethanol solutions with the concentrations from 0 to 3.0% (corresponding to change in refractive index $\Delta n=1.34\times10^{-3}$/wt%). The characteristics of a single MRR were also measured. In the measurements, a flow channel made of polydimethylsiloxane (PDMS) was set on the sensor chip and the ethanol solutions were poured through it. Then the transmittance of laser lights with TE polarization was measured using an optical spectrum analyzer. Fig. 3(a) shows the measured transmission spectra of the MRR-MZI at around 1550 nm wavelength region for sensing ethanol solutions. The transmittance at 1536.95 nm was markedly changed by changing the concentration of ethanol. Fig. 3(b) shows the measured light transmittance of the MRR-MZI at 1536.95 nm as a function of ethanol concentration. For comparison, the measured transmittance of a single MRR is also plotted. The changes in light transmittance of 0 to 1% concentration for the MRR-MZI and single MMR are 8.9 and 5.9 dB, respectively. That is, the MRR-MZI has a higher sensitivity by 3.0 dB than the single MRR at low ethanol concentration. In this measurement, the extinction ratio of the MRR-MZI is relatively small due to the imbalance between light powers in both arms.

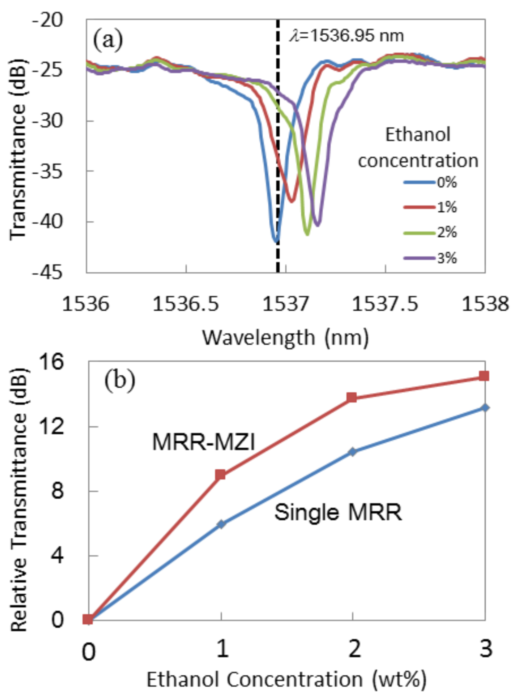

Fig. 3. (a) Measured transmittance spectra of MRR-MZI. (b) Measured relative transmittance of MRR-MZI and single MRR.

Next, we investigated the sensing characteristics for a biotin solution. Avidins were fixed on the surface of the microring waveguide through biotin-PEG-NHS (Fig. 1(b)). By comparing the light transmission of the avidin-fixed MRR-MZI with that without avidin, the existence of avidin in the solution can be detected.

Fig. 4 shows the measured transmission spectra of the MRR-MZI for sensing avidin solutions. The transmission spectrum was shifted to a longer wavelength direction when avidin was fixed. The maximum change in transmittance of 3.6 dB was obtained at the wavelength of 1554.04 nm. This result indicates that the proposed MRR-MZI is very promising for highly-sensitive biosensing based on the change in transmittance. The change in transmittance can be further increased by adjusting the light power balance in both MZI arms, and it will be possible to detect avidin with the concentration of less than 10 pM.

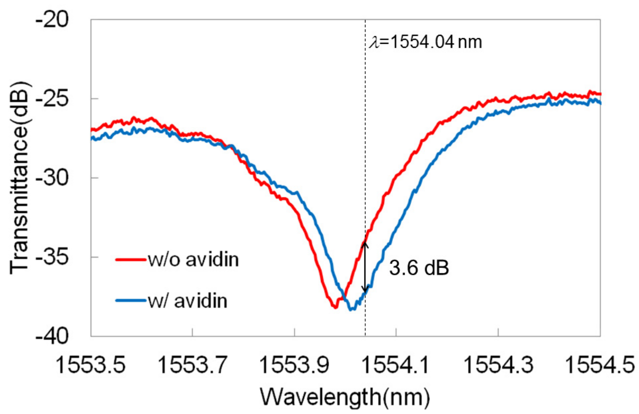

Fig. 4. Measured transmittance spectra of MRR-MZI for 20 pM-avidin solution.

4. Conclusions

We have demonstrated an optical biosensor based on a silicon MRR-MZI. Its sensing characteristics are investigated using ethanol solutions and avidin/biotin solutions. The MRR-MZI has higher sensitivity than a single MRR sensor, and avidin with the concentration of as low as 20 pM is successfully sensed by the proposed MRR-MZI. The results show that the MRR-MZI sensor is promising for high-sensitivity biosensing.

Acknowledgements

We are grateful to Prof. T. Ogino, Yokohama National University, for helping the avidin/biotin experiments, and to Dr. S. Kita, Harvard University (currently NTT basic research laboratories), for his fruitful discussion. This work is partly supported by the Grant-in-Aid for Scientific Research B, MEXT, Japan (No. 15H03577).

References

[1] J. Homola, Chem. Rev. **108** (2008) 462.
[2] C. Barrios *et al.*, Opt. Lett. **33** (2008), 708.
[3] S. Kita *et al.*, Opt. Express **16** (2008) 8174.
[4] D. Dorfnera *et al.*, Biosens. Bio. **29** (2009) 3688.
[5] S. Nacer and A. Aissat, Opt. Quant. Electron. **44** (2012) 35.
[6] K. Vos *et al.*, Opt. Express **15** (2007) 7610.
[7] M. Fukuyama *et al.*, Jpn. J. Appl. Phys. **49** (2010) 04DL09.
[8] H. Kaneshige *et al.*, Opt. Express **21** (2013) 16888.