Silicon Photonics Technology and Application to Optical Bio Sensor

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An increasing number of companies are working on the Sustainable Development Goals (SDGs), which are seventeen common goals set down for the international community to achieve by 2030. In an effort to take part in solving the social issues listed in the SDGs, OKI is taking on challenges of expanding its technologies into new fields. One challenge aims at applying OKI's silicon photonics technology, developed for optical communication, to an ultra-compact optical bio sensor used in healthcare enabling such application as high-precision real-time sensing of viruses.

Silicon photonics technology applies complementary metal oxide semiconductor (CMOS) technology used for mass production of CPUs and memories to the low-cost production of ultra-fine optical circuits mainly made of silicon onto silicon on insulator (SOI) wafers. A bio sensor is a general term for chemical sensors that utilize molecular recognition mechanism of a biological origin. The basic principle is to convert the unique reaction of a biomolecule such as an antigen-antibody reaction into an electric signal and detect the signal. The part that converts this unique reaction into an electric signal by some means is called a transducer, and this is the part where silicon photonics technology can be applied.

As a light-based bio sensor, a sensor using surface plasmon resonance (SPR) has been put into practical use, but for measuring the angle dependence of reflected light, the device becomes large. On the other hand, if silicon photonics is used, the bio sensor in theory will have no moving parts, and the device is expected to be compact. Furthermore, since the sensor chip is extremely small, arraying the sensor chips will make it easy to take large number of simultaneous measurements.

Since biotechnology depends on the substance to be measured and the variety of targets is numerous, this article primarily introduces the silicon photonics technology, which will serve as a base technology that is independent of the measurement target.

Overview and Achievements of Silicon Photonics

A major feature of silicon photonics is that by using silicon as a base, not only passive elements such as optical waveguides and wavelength multiplexing/demultiplexing filters, but also active elements that are electrically driven such as modulators and photo detectors can be formed at the same time. OKI is aiming to apply this advantageous feature to ultra-compact optical transceivers for the Internet of Things (IoT) network and is proceeding with efforts for the technological development of silicon photonics including participation in the "Development of Technologies for Super Energy-Efficient Optical Electronics Implementation Systems" (previously known as "Integrated Photonics-Electronics Convergence System Technology") project commissioned by the New Energy and Industrial Technology Development Organization (NEDO)[1].

Figure 1 shows the configuration of the developed single-core bidirectional optical transceiver chip and a photograph of the prototype module. In order to accommodate the enormous communication capacity of the 5th generation mobile network expected to serve as the access network for IoT, the integrated chip is configured to handle time and wavelength division multiplexing (TWDM) that combines wavelength multiplexing of four wavelengths each for both the uplink and downlink[2]. Many optical functional devices have been developed through the Development of Technologies for Super Energy-Efficient Optical Electronics Implementation Systems project, but among them, the wavelength filter that realizes polarization independence and the highly sensitive avalanche photodiode (APD) that can internally amplify weak signals are great achievements in their unique structures[3) 4)]. They are important devices that can be used for the basic configuration of optical bio sensors. Since it is physically difficult to realize a silicon-based light source, a separately prepared semiconductor laser array is flip-chip mounted.

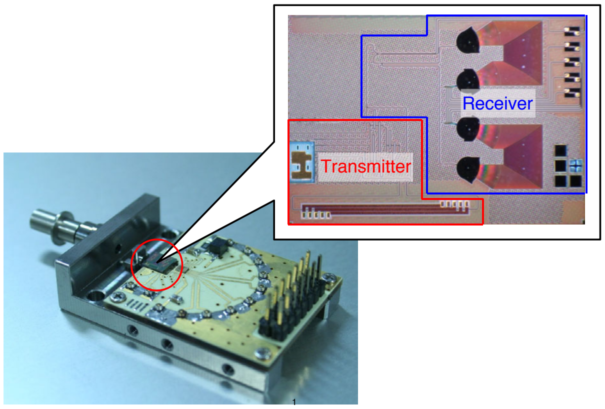


Figure 1. TWDM-PON Transceiver Module and Chip Configuration

Optical Bio Sensor Using Silicon Photonics

In this article, an optical bio sensor is defined as a sensor device that combines "biotechnology that selectively adsorbs the substance to be measured and causes a structural change (refractive index change)" with "silicon photonics technology that detects minute changes in the refractive index and converts the optical changes into electrical signals at the photo detector."

The change in the refractive index that occurs in biotechnology is basically detected with the wavelength shift of the MZI or ring resonator. MZI is a device that divides incident light into equal parts, adds a difference in refractive index to one, then combines them, and detects the phase difference as a change in light intensity. Since the refractive index change in biotechnology is small, it is necessary to increase the optical path length to several millimeters in order to obtain a sufficient phase difference, which increases the device size. On the other hand, the ring resonator has a very small radius of about several 10μm and a very high Q factor (sharpness index of the resonance wavelength peak), and therefore a large intensity change can be obtained even with a minute wavelength shift. Considering the batch simultaneous inspection by arraying in the future, the ring resonator was selected as the basic structure in this study.

Next, the configuration and principle of the optical bio sensor using a ring resonator will be described. **Figure 2 (a)** is an electron micrograph of the ring resonator. The ring resonator is placed in the vicinity of the linear waveguide. Only the resonance wavelength of the incident light is coupled to the ring resonator via the directional coupler. The resonance wavelength that circles the ring resonator is represented as:

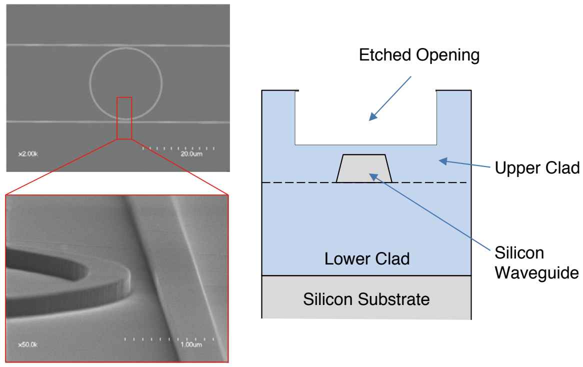
$$\lambda_{res} = \frac{2\pi n_{eff} R}{m}$$

n_{eff} is the equivalent refractive index of the optical waveguide, R is the radius of the ring resonator, and m is the order of the resonance mode. Since the resonance wavelength is proportional to the equivalent refractive index, search for a structure in which the change in the equivalent refractive index is large was a major design principle. **Figure 2 (b)** is the cross-sectional structure of the ring resonator's waveguide. The upper clad directly above the optical waveguide was etched to form an opening.

Figure 3 shows the operating principle of an optical bio sensor using such a ring resonator. In the opening formed on the clad, antibody is fixed onto the silicon waveguide via an antibody-binding protein called Si-tag[5] (**Figure 3 (a)**, **Figure 3 (b)**). At this time, if the antigen to be detected is captured by the antibody via a separately formed microchannel, the refractive index around the waveguide changes instantaneously in proportion to the concentration (**Figure 3 (c)**). The change in the equivalent refractive index when the refractive index around the waveguide changes is represented as:

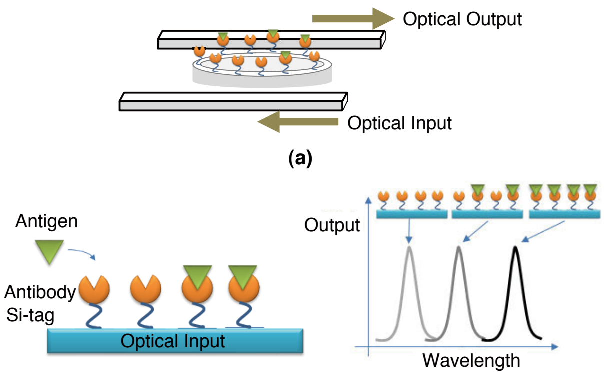
$$\Delta n_{eff} = \iint |E(x,y)|^2 \Delta n(x,y) dxdy$$

Therefore, the larger the portion where the spatial distribution $\Delta n\ (x, y)$ of the refractive index change and the electric field distribution $E\ (x, y)$ of light overlap, the larger the change in the equivalent refractive index and the observed wavelength shift. Considering the cross-sectional structure of **Figure 2 (b)**, it is clear that the influence of the electric field component (evanescent wave) exuded from the silicon waveguide to the upper part of the clad is large. Hence, the etching depth of the upper clad and its reproducibility are important control parameters of the device structure.



(a) (b)

Figure 2. Optical Bio Sensor Structure



(b) (c)

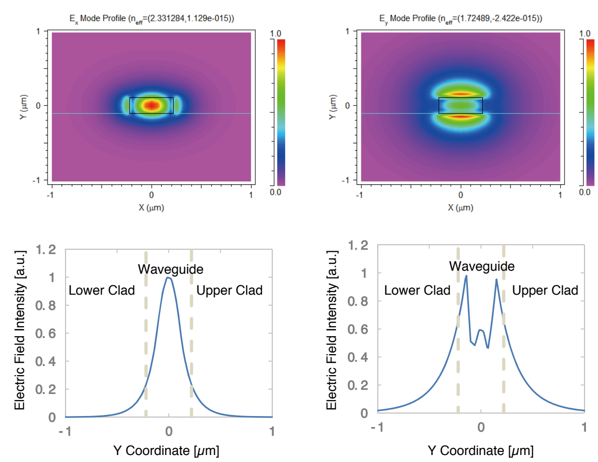
Figure 3. Optical Bio Sensor Operating Principle

Optical Bio Sensor Design and Prototype

As mentioned in the previous section, the amount of wavelength shift and the magnitude of the Q factor due to the change in the refractive index are important factors in the design of the ring resonator optical bio sensor.

The optical waveguide used in this study has a flat cross-sectional shape with a width of 440nm and a height of 220nm, and has polarization dependence. That is, the propagation characteristics differ greatly between the transverse electric (TE) mode in which the electric field is in the horizontal direction and the transverse magnetic (TM) mode in which the electric field is in the vertical direction. In the normal communication band, the TE mode is commonly used for its ease of handling, but in this study, the TM mode was used. This is because when an opening is made on the waveguide, the TM mode provides a larger sense of change in the refractive index. **Figure 4 (a)** and **Figure 4 (b)** show the electric field distribution in the TE and TM modes, respectively. Comparing the two, it is clear that the TM mode has a wider distribution in the vertical direction of the waveguide.

Figure 5 shows the relationship between the remaining un-etched thickness of the measured opening and the wavelength shift coefficient. It can be confirmed that sensitivity of the TM mode is higher than that of the TE mode, and thinner the remaining thickness, larger the wavelength shift coefficient and higher the sensitivity. It is ideal to remove all the clad directly above the silicon waveguide, but in practice, it is better to leave a slight upper clad considering the in-plane uniformity and damage during etching.



(a) (b)

Figure 4. TE and TM Modes

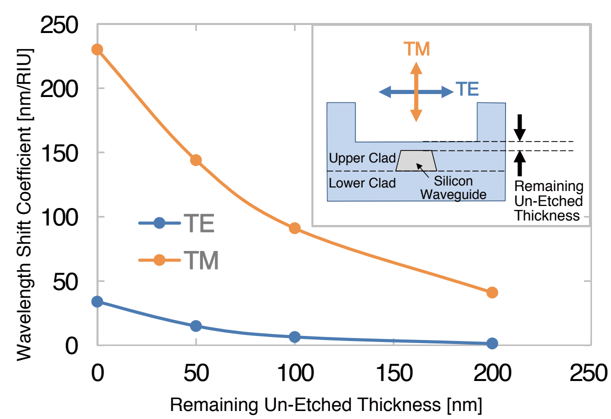


Figure 5. Wavelength Shift Coefficient and Remaining Un-Etched Thickness

Next, in order to obtain the wavelength shift coefficient, the refractive index dependence of the ring resonator's resonance wavelength was investigated. The refractive index change was simulated using a refractive index regulating fluid (n=1.49, 1.50, 1.51, 1.52). For the measurement, a ring resonator with a remaining un-etched thickness adjusted to 50 nm or less was used.

From the measurement results of the ring resonator's transmission spectrum shown in **Figure 6 (a)**, peak wavelength was plotted against the refractive index (**Figure 6 (b)**). The slope represents the wavelength shift coefficient, which is approximately 224nm/RIU. This value is roughly in agreement with the calculated value in **Figure 5**. The Q factor estimated from the half width of the resonance peak in **Figure 6 (a)** was about 4000. This value is reasonable for a silicon ring resonator, but it is not considered high. The value can be expected to increase another digit by reducing the propagation loss, increasing the resonator length, and reducing the coupling efficiency[6].

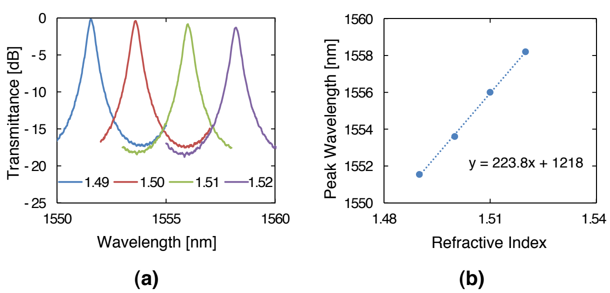


Figure 6. Refractive Index Change and Resonant Wavelength Shift

Finally, an optical bio sensor modularized for easy use is introduced. An optical bio sensor module was prototyped by attaching input/output optical fibers, coupling lenses, and a Peltier element for temperature control to an optical bio sensor chip (Si photo chip) with good characteristics (**Figure 7**). This made it possible to actually evaluate an antigen-antibody reaction. It has been confirmed that there is no significant change in the characteristics before and after modularization, and a detailed evaluation of the ring resonator device can easily be performed.

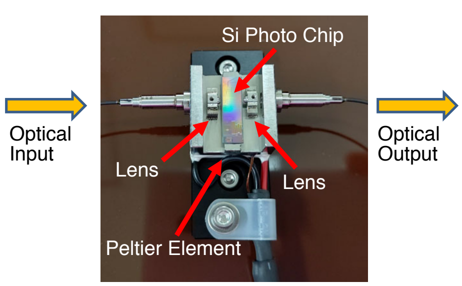


Figure 7. Modularized Optical Bio Sensor

Conclusion

OKI has examined the expansion of its silicon photonics technology, which has been developed for optical communication, to the healthcare field. A basic evaluation of a fine ring resonator using silicon photonics technology was performed, and confirmation was made for possible realization of an ultra-compact or multi-channel optical bio sensor. OKI is aiming to enable highly accurate real-time sensing of viruses and applying it to manage daily physical condition and to prevent the spread of infectious diseases. Additionally, it is expected the technology can be applied to the sensing of allergens, environmental hormones and others in which antigen-antibody reaction can be used. Study is also being conducted to use the technology for odor detection, which is expected to have a wide range of applications such as in food items, medical care, and security.

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TIPS 【Glossary】

Silicon photonics
Technology that uses complementary metal oxide semiconductor (CMOS) for high density integration of optical functional elements mainly made of silicon onto an SOI (Silicon On Insulator) substrate.

Flip-chip mounting
A method that flips the semiconductor LD chip for mounting. Since the electrodes on the silicon photonics integrated chip and the electrodes formed on the surface of the semiconductor LD are directly bonded via solder bumps, no wire is required and the mounting area can be reduced.

Antigen-antibody reaction
A reaction caused by a unique binding between a foreign substance (antigen) that has invaded a living body and an antibody, and it is also referred to as an immune reaction.

Q factor (Quality factor)
Represents the sharpness of the resonance wavelength of a resonator. Represented as

$$\text{Q factor} = \frac{\lambda_0}{FWHM}$$

where $\lambda 0$ is resonance wavelength and FWHM is the half width.