Silicon Slot Waveguide based Bulk Refractive Index Sensing of Electrolyte and Carbohydrate

(Student Paper)

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ABSTRACT

In this paper, we present a slot waveguide-based on-chip bulk refractive index sensing of liquids. We experimentally demonstrate a slot-based ring resonator with a spectral sensitivity of 363 nm/RIU. We experimentally show sensing of refractive index potassium chloride various concentration and verified with Abbe refractometer. Finally, we experimentally investigated simultaneous absorption and refractive index sensing of glucose.

Keywords: slot waveguide, ring resonator, absorption sensing, photonic integrated circuit, silicon photonics.

1. INTRODUCTION

Photonic integrated circuits (PIC) as a sensor platform for sensing has drawn much attention in recent years. This is mainly because it enables the integration of several optical components on a single chip. On-chip integration of optical components has opened avenues for cost effective and scalable on-chip sensors for medical diagnostics, environmental and food quality monitoring [1-4]. Silicon PIC based sensors are typically realised on silicon-on-insulator (SOI) substrate, as silicon is transparent in the near infrared. Additionally, the compatibility of silicon with CMOS processes enables large-scale integration and volume production. Furthermore, the high index contrast allows compact photonic circuits, enabling sensor arrays for multiplex sensing on a single chip.

An important criterion for PIC sensor is the measurable change in the optical spectrum because of the compositional or density change in the environment (refractive index). In PIC, the transduction is based on the interaction of the evanescent wave of a guided mode with the environment. A perturbation in the environment is sensed by the evanescent wave, that causes a change in the waveguide parameters such as effective refractive index (n_{eff}) and group index (n_g). These waveguide parameters can be measured using interference/resonance-based devices such as ring resonators or Mach-Zehnder interferometers(MZI). Compared to MZI, ring resonator offers the advantages of higher sensitivity and smaller footprint for dense integration of sensors. Ring resonators based on wire waveguides have been demonstrated for biosensing because of their capability to achieve very low detection limit [3]. This is mainly attributed to their sharp resonance that allows accurate measurements of the spectral shift. In addtion, the strong field enhancement near the surface makes it highly attractive for surface sensing. However, wire-based ring resonators have a low spectral shift (in the orders of 100 nm/RIU) [3,4] because of their low spatial field overlap with the bulk environment. Thereby, it limits wire-based ring resonators for bulk sensing applications. Recently, slot waveguide has attracted much attention due to its inherent ability to guide light in a low index medium [1,5,6]. Unlike wire waveguides, slot waveguides have the advantage of increased spatial overlap of the evanescent and sensing environment, resulting in a higher sensitivity (nm/RIU). Hence, slot waveguides are highly attractive for bulk index sensing applications.

In this paper, we demonstrate bulk refractive index sensing using slot waveguides. The refractive index measurement is studied using different concentrations in various fluids such as potassium chloride (KCL), an electrolyte and glucose, a carbohydrate. We experimentally demonstrated both absorption and refractive index sensing of glucose by monitoring the quality factor and wavelength shift at different concentrations of glucose.

2. Principle of Operation

Figure 1 shows a schematic of a slotted ring resonator. The inset shows the cross-section of a slot waveguide and the corresponding electric field distribution in water. In a ring resonator structure, the light propagating through the straight waveguide is evanescently coupled into the ring. The wavelengths that satisfy the resonant condition ($m\lambda = 2\pi n_{eff}R$) resonate inside the ring. The wavelength sensitivity due to the variation of the cladding refractive index (Δn_{cl}) can be observed by a shift in resonant wavelength ($\Delta\lambda$). The wavelength sensitivity can be expressed as a wavelength shift per unit change in the bulk refractive index of cladding (with units of nm/RIU), given by [4],

$$S = \frac{\Delta\lambda}{\Delta n_{cl}} = \frac{\lambda_o}{n_g}\frac{\partial n_{eff-cl}}{\partial n_{cl}} \quad (1)$$

Where n_{eff} and R are the effective refractive index and the radius of the ring. In (1), $\Delta n_{eff\text{-}cl}$ is the change in the effective index because of the change in the cladding index (Δn_{cl}).

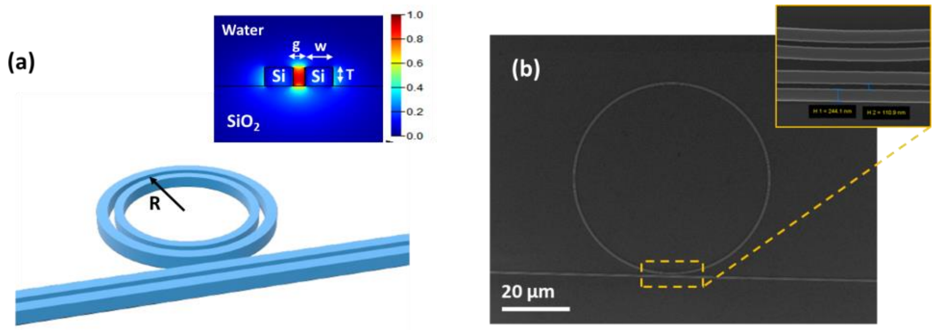

Figure 1. Schematic of slot waveguide-based ring resonator. Inset shows the simulated electric field distribution of an SOI slot waveguide in water, slot rail width (W)= 240 nm, gap (g) = 110 nm and thickness (T)= 220 nm. (b) SEM image of the fabricated slotted ring resonator, inset showing close-up view of the coupling region between the slotted ring and the bus waveguide.

3. Results and Discussion

The fabrication of slot-based ring resonator is done on SOI platform with 220 nm device layer and 2000 nm buried oxide. The fabrication involved patterning of slotted waveguides using electron beam lithography (e-beam) followed by Reactive-Ion-Etching (RIE) of 220 nm of silicon. A second e-beam lithography is performed to pattern the grating couplers followed by 70 nm etch of silicon in RIE. Figure 1(b) shows the SEM image of the fabricated device. The inset shows the coupling region of the slotted bus and ring having a radius R= 29.69 µm. A tunable laser and a photodetector are used to characterise the optical spectrum of the device. The temperature of the device is maintained at 27 ºC using a Peltier thermoelectric cooling element.

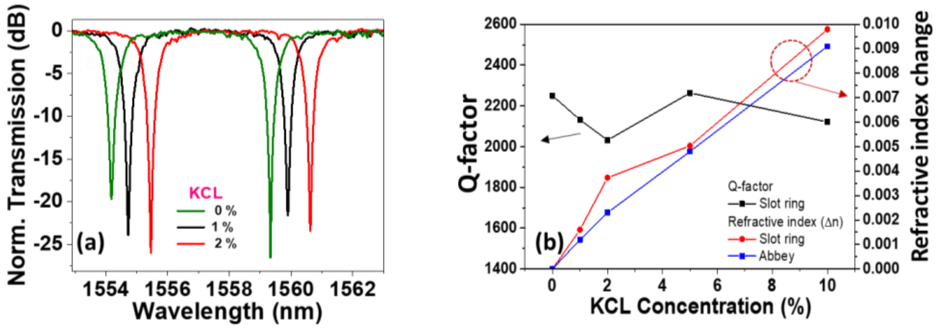

Figure 2. (a) Transmission response of the slotted ring resonator at different KCL concentrations; (b) The quality factor (Q-factor) and the refractive index change at different KCL concentrations measured using slotted ring resonator and Abbe refractometer.

Figure 2(a) shows the transmission response of the ring resonator for different consecrations of KCl. The measured free spectral range is 4.66 nm, and the corresponding group index is 2.765 at 1550 nm wavelength. Using (1), the cladding refractive index is calculated and compared with the Abbe refractometer measurement. Figure 2 shows an excellent agreement between slot-ring measurement and refractometer measurement. Based on this, we measured a sensitivity of 363 nm/RIU. The extracted quality factor (Q-factor) of the ring at different KCL concentrations indicates no sign of degradation (Fig. 2(a)) that suggest that there is negligible absorption increase at 1550 nm wavelngth band with concentration. The same experiment is performed for glucose with different concentrations as shown in Fig. 3. The ring response for different glucose concentrations is shown in Fig. 3(a,b); the Q-factor is reduced by almost half. This indicates that the presence of glucose causes attenuation of light which results in lower Q-factor of the ring resonator. The attenuation is due to broad absorption of glucose around 1550 nm band [2, 7]. Slot waveguides offer simultaneous measurement of absorption and refractive index change offers multi parameter sensing. Furthermore, resonance cavity reduced the effective device footprint as well.

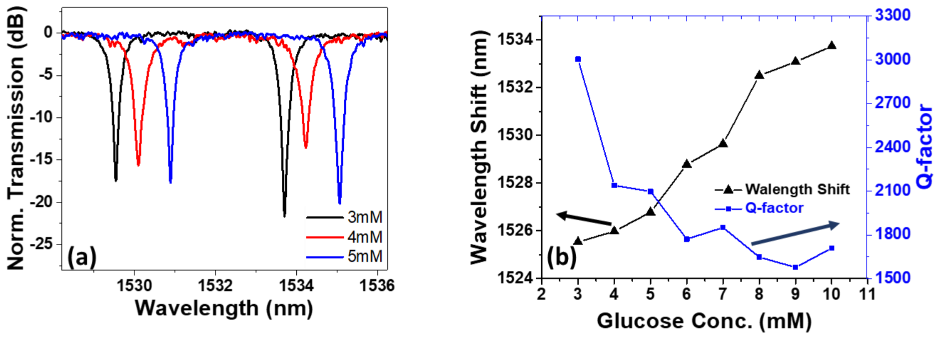

Figure 3. (a) Transmission response of the slotted ring resonator at different glucose concentrations (b) Wavelength shift and the extracted Q-factor at different glucose concentrations.

4. CONCLUSIONS

In this work, we presented a highly sensitive slot waveguide bulk index sensing platform with sensitivity of 363 nm/RIU. We experimentally demonstrated refractive index measurement of KCL and verified using Abbe refractometer. Finally, we demonstrate a simple approach for absorption and refractive index-based monitoring of glucose concentration.

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