HIGH SENSITIVITY AND LARGE MEASUREMENT RANGE REFRACTOMETRIC SENSING BASED ON MACH-ZEHNDER INTERFEROMETER

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ABSTRACT

An on-chip refractive index (RI) sensor with high sensitivity and large measurement range is demonstrated. The sensing scheme presented here is based on Mach-Zehnder interferometer configuration built on an SOI wafer. The measured wavelength sensitivity reaches 3498.6 nm/RIU (TE-mode). Meanwhile, according to the period changes of interference patterns, the measured period sensitivities are 20.4 nm/RIU (TE-mode) and 61.1 nm/RIU (TM-mode), respectively. Therefore, the fine index change detection limit reaches up to 1.1×10^{-5} RIU, while the period shift for larger index change detection has a measurement range of several RIU. By making an array, the proposed on-chip sensor has a potential application for multiple samples detection, such as chemical and bio-toxins in drinking water ranging from sub-nanogram to picogram level.

INTRODUCTION

Refractive index sensing normally detects refractive index (RI) change of the surrounding material caused by the concentration change of chemical [1] or bio-sample [2]. In the past, fiber-based RI sensors have been widely investigated [4, 5], which provide increasing sensitivity. On the other hand, silicon nano-photonics has been the emergence to be a promising method to create on-chip optical systems at an unprecedented scale of integration. The advantages of silicon photonics enabled index change detection in terms of high sensitivity, fast response, and real time measurement in a very small footprint appealing to a wider application. Moreover, fabrication of silicon photonics sensors is CMOS compactible, which is easy to integrate all optical blocks and electrical signal processing elements onto the same chip. It therefore significantly reduces device footprint and manufacturing cost.

Mach-Zehnder interferometers (MZIs) are optical devices, which use the interference between two optical signals from the same origin source, travelling along different effective optical path length [6, 7]. Such devices/ configurations have been widely used in the photonics integrated circuits as a building block. With a tiny change in optical path length, a larger and easier quantified output can be produced. Thus, high sensitivity to the RI changes and high-resolution response can make it a promising device for multiple parameters detection.

In this paper, a Mach-Zehnder interferometer based photonic refractometer is proposed, showing a wide measurement range with high sensitivity.

DESIGN AND THEORY

Figure 1 schematically shows the sensor unit based on Mach-Zehnder interferometer configuration, which is built on the SOI substrate. After light coupled into the input waveguide, it splits equally through a Y-branch (Figure 3) into the upper sensing arm and bottom reference one. The final interference pattern is measured at the output side. The designed Y-branch presents an ultra-low loss of less than 0.28 dB [3]. The waveguide structure has a dimension

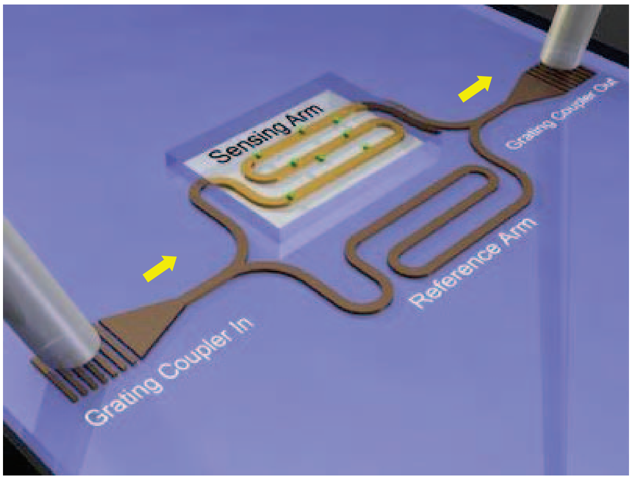

Figure 1: Schematic of Mach-Zehnder interferometer sensing unit. Upon sensing arm has an opening window to expose waveguide to the environment.

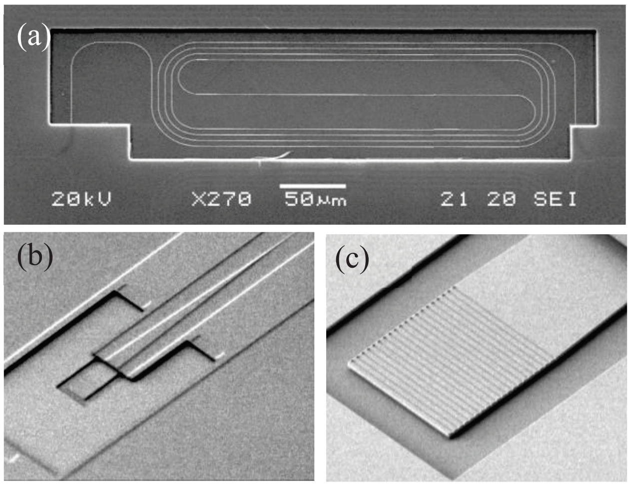

Figure 2: (a) SEM image of the sensing arm, formed in a snakelike loop; and (b & c) the grating coupler structure.

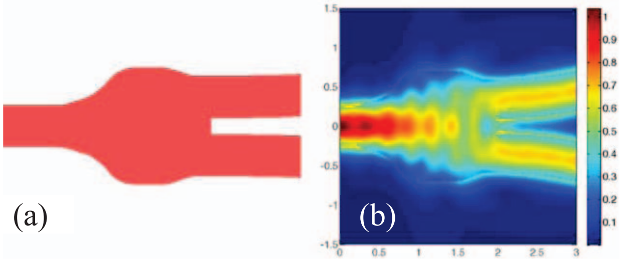

Figure 3: (a) Schematic of the ultra-low loss Y-branch used, which is designed by particle swarm optimization. (b) Light field inside the Y-branch structure.

of 500 nm × 340 nm (width × height). The sensing and reference arms, formed in a snakelike loop on the SOI substrate, have a total length of 5 mm and 4.9 mm, respectively. Figure 2 shows the SEM images of the fabricated device and the grating coupler used. In principle, any refractive index (RI) change in the sensing area (e.g. within the sensing window) can be detected through the spectrum (i.e. interference pattern variations). It can be further quantified through Fast Fourier transform. Therefore, the proposed sensor shows great potential to measure multiple concentrations of chemical and biochemical molecules in drinking water.

In principle, the length unbalance of the sensing arm and the reference arm forms sinusoidal interference spectrum. In particular, the constructive interference condition is expressed as

$$n_{eff1}(\lambda, \mathrm{n}_{clad})L_1 - n_{eff2}(\lambda)L_2 = \lambda_0 m, \qquad (1)$$

where m = 1,2,3,… λ is the light wavelength. n_{clad} means the RI of cladding material in the sensing window. L_1 and L_2 are the length of the sensing arm and reference arm, respectively. n_{eff} means effective index. From the above governing equation, RI change in the sensing area could cause optical path length change, and subsequently the optical path length difference affects the interference pattern. As a result, the destructive interference peaks shift. Here, the wavelength sensitivity of the sensor is defined by the interference peak wavelength shift and the cladding RI change, as

$$S_\lambda = \frac{\Delta\lambda}{\Delta n_{clad}} = \frac{\lambda_0}{n_{g1} - n_{g2}\dfrac{L_2}{L_1}} \cdot \frac{\partial n_{eff1}}{\partial n_{clad}}, \qquad (2)$$

where n_g is group index. The wavelength sensitivity for current device can be calculated by above equation. According to simulation, it is estimated that S_λ = 654 nm/RIU and S_λ = 2336 nm/RIU for TE- mode and TM-mode respectively.

Since the period of the spectrum is also a function of cladding RI, so the period can also be used for sensing. Here, the period sensitivity defined as

$$S_T = \frac{\Delta T}{\Delta n_{clad}}, T = \frac{\lambda_0^2}{L_1 \mathrm{n}_{g1} - L_2 \mathrm{n}_{g2}} \qquad (3)$$

Therefore, in order to improve sensing performance (e.g. high sensitivity) , increasing the length difference between sensing arm and reference one, and design a structure that is sensitive to the cladding material RI change would be preferred methods.

In our sensor design, the 340-nm thickness and 500-nm width waveguide support both TE-mode and TM-mode. Since TE-mode and TM-mode have different group index, they present two different periods corresponded to TE-mode and TM-mode present in the device spectrum. These can be distinguished by proforming fast Fourier transform to the spectrum. Additionally, the two modes have different sensitivities, which can be used to complement each other.

FABRICATION PROCESS

The MZI device is fabricated by standard Complementary metal-oxide semiconductor (CMOS) process, as shown in Figure 4. 8-inch silicon-on-insulator (SOI) wafer is used. Thickness of the silicon structure layer is 220 nm and the buried oxide layer is 2 μm. Firstly the grating coupler is patterned by 248-nm deep UV lithography and reactive ion etching (RIE) process. Then the waveguide is patterned by the same method with silicon dioxide on top as hard mask. Followed by 1.5-μm thickness silicon dioxide cladding deposition by Plasma-enhanced chemical vapor deposition (PECVD), which is used as a protection and reduce loss. Then the sensing windows are opened. Finally, dicing line is formed by DRIE process.

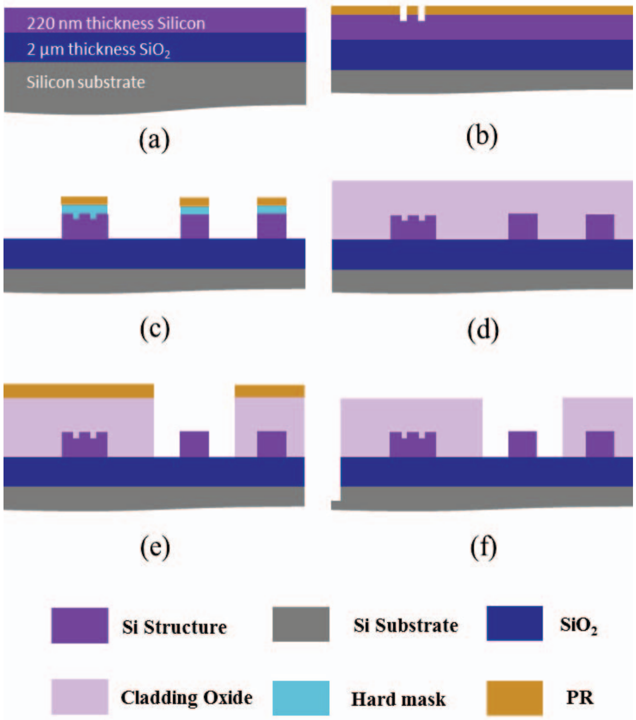

Figure 4: Fabrication process of the Mach-Zehnder Interferometer device. 1) Starting SOI wafer. 2) Grating coupler etch. 3) Waveguide etch. 4) Oxide cladding by PECVD. 5) Window pattern and etch. 6) Deep trench etch.

RESULTS AND DISCUSSIONS

The refractometric response is characterized by covering the chip surface with refractive index liquid (Cargille Laboratories). Figure 5 shows the measured spectrum response with respect to the RI changes. The lines from bottom to top represent the refractive index changing from 1.508 to 1.556 RIU with an increment of 0.008 RIU. By using fast Fourier transform and chirp Z-transform to refine the results, the fluctuation frequency in each conditions are plotted, as shown in Figure 6, mainly showing two peaks of TE-mode and TM-mode. With the RI increase, the TE-mode and TM-mode peak both left shift. Further calculations (according to peaks positions in Figure 6) plot the relationship between periods and the RI detection as shown in Figure 7. It illustrates the period sensitivities are 20.4 nm/RIU and 61.1 nm/RIU for TE-mode and TM-mode, respectively. Both sensitivities can be used to determine the large shift of RI, with the detection limit of 6.0×10^{-4} RIU (TE) and 3.7×10^{-4} RIU (TM) respectively. The measurement range can reach to 2-3 RIU, depending on the linewidth of the laser used. Figure 8 shows the transmission spectrum of TE mode only. The corresponding peak position blue shifts (left shift) as RI increases. The corresponding wavelength shift is plotted in Figure 9. The sensitivity is 3498.6 nm/RIU, which can be used to measure the fine RI change, with the detection limit of 1.1×10^{-5} RIU. Thus, by combining the period and wavelength measurements, the sensor provides a large RI detection range with high sensitivity of 3498.6 nm/RIU.

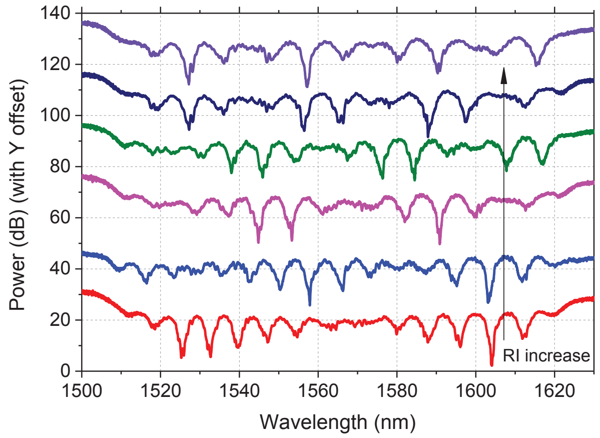

Figure 5: The transmission spectrum response of the on-chip refractometry sensor, as RI changes. The refractive change from 1.508-1.556 with increment of 0.008 from bottom to top.

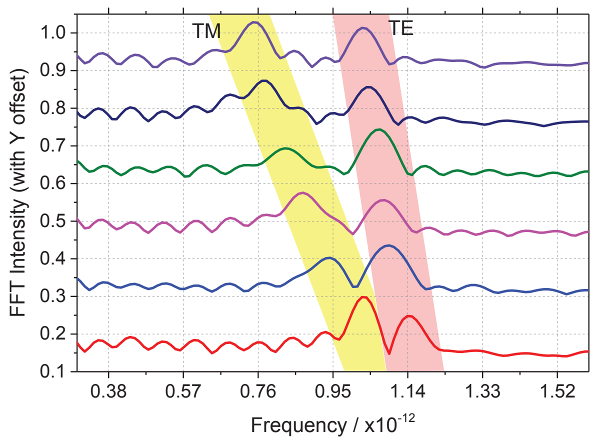

Figure 6: Fast Fourier transform result of the corresponding spectrum in Fig. 5. The peak position represents the spectrum period (TE- and TM-mode). The refractive change from 1.508-1.556 with increment of 0.008 from bottom to top.

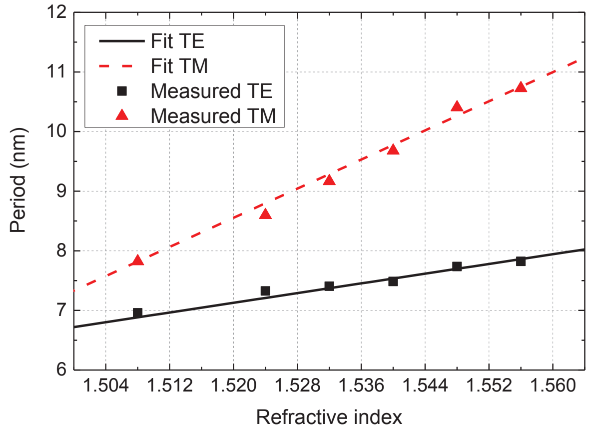

Figure 7: The period vs measured refractive index.

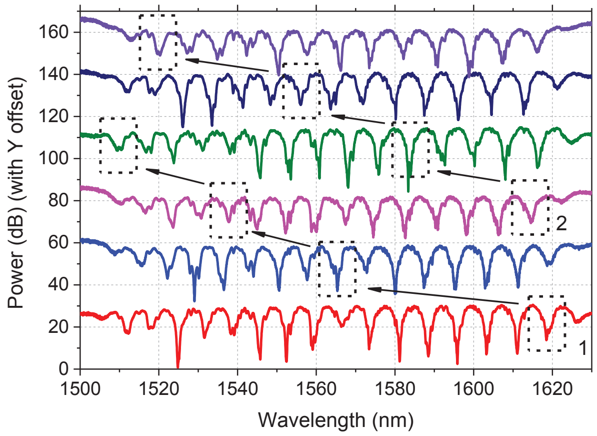

Figure 8: The TE mode transmission spectrum at different RI levels. Two peak shift is marked with dot box. The refractive change from 1.508-1.556 with increment of 0.008 from bottom to top.

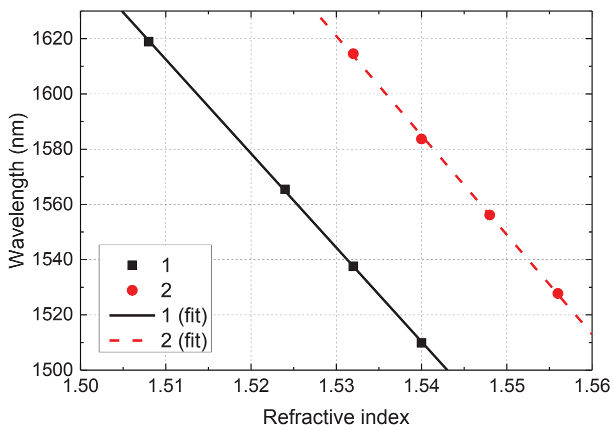

Figure 9: Two corresponding peak shift when RI change.

CONCLUSIONS

In summary, a photonics on-chip refractive index sensor based on MZI structure is demonstrated. In terms of wavelength sensitivity, it is estimated to reach 3498.6 nm/RIU (TE mode). The period sensitivities are 20.4 nm/RIU (TE-mode) and 61.1 nm/RIU (TM-mode) for TE-mode and TM-mode, respectively. Through combination both TE-mode and TM-mode responses, the proposed refractive index sensor has potential to achieve a high sensitivity and large measurement range. This refractive index sensor offers a potential applications and opportunities for multiple parameters detection, such as chemical and bio-toxins in drinking water at sub-nanogram- to pictogram- level.

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