A Novel Sensing Scheme Based on Resonance Splitting in Silicon Microrings

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We propose a novel waveguide sensor based on a large SOI microring resonator with intentional peak splitting introduced by an MZI reflector inside the ring. It combines the advantages of both ring resonator and MZI based sensors. The novelty lies in that it tracks the change in peak splitting rather than the change in absolute resonance wavelength.

Introduction

Sensing is one of the most attractive applications of photonics integrated circuits (PICs) [1–5], and silicon photonics has proven to be a quite promising platform for this application due to its CMOS compatibility and high index contrast. Among silicon photonics devices, ring resonators and Mach-Zehnder-Interferometers (MZIs) are the most commonly used to demonstrate sensing applications. Ring resonators have advantages of a very narrow bandwidth, leading to a high sensitivity [4,5]. But sensing range is within the free spectral range (FSR), and rings can be sensitive to temperature-induced noise. MZI-based sensors can benefit from the temperature insensitivity as the temperature induced index change would cancel out if the MZI are designed to be balanced [1, 2]. However, they have the drawback of a broad bandwidth.
In this paper, we propose a new structure and scheme for silicon waveguide sensors. It consists of both ring and MZI, combining advantages of both device types. The basic principle is the reflection induced resonance splitting of a ring resonator. The split distance is proportional to the reflection inside the ring, which couples the clockwise and counterclockwise mode. We intentionally introduce a loop-MZI reflector in the ring, which incorporates the sensor waveguide. A small change in the sensor waveguide will introduce a significant change in the MZI reflectivity, which will in turn affect the peak splitting in the ring transmission spectrum. Consequently we can track the split distance to detect the change of environment index.

Schematic and Theory

The basic schematic of this device is shown in Fig.1. The idea originates from the research of backscattering in microrings [6]. Any kind of reflection inside a ring could couple the two circulating modes and results in a resonance splitting. For most applications, splitting will be problematic as it's not predictive and controllable. However, resonance splitting can be a powerful instrument and turn out to be beneficial if it can be fully controlled, for instance, in the sensing application presented in this paper.

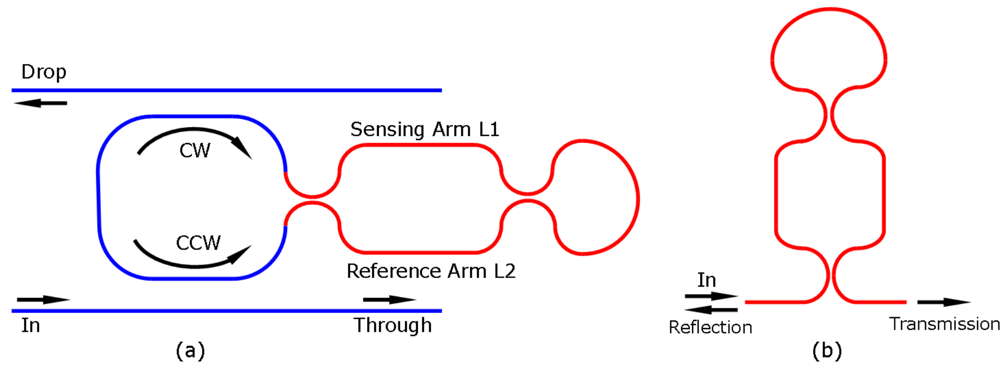


Figure 1: The schematic of (a) the ring based sensor and (b) the MZI based reflector. One of the MZI arm will be exposed to the sensing environment.

The theory about resonance splitting is already explained in detail in [6,7], briefly speaking, the distance between the split peaks in the frequency domain $\Delta\omega$ is related to the reflectivity in the following equation:

$$\Delta\omega = 2\frac{r_0 c}{n_g L} cos(\frac{\phi_\mu}{2}) \quad (1)$$

Where r_0 is the field reflectivity, c light speed in vacuum, n_g group index of the waveguide and L ring's physical length. For simple coupling, we find that $\phi_\mu = 0$. A more straightforward equation (2) could be generated after simple transformations of (1):

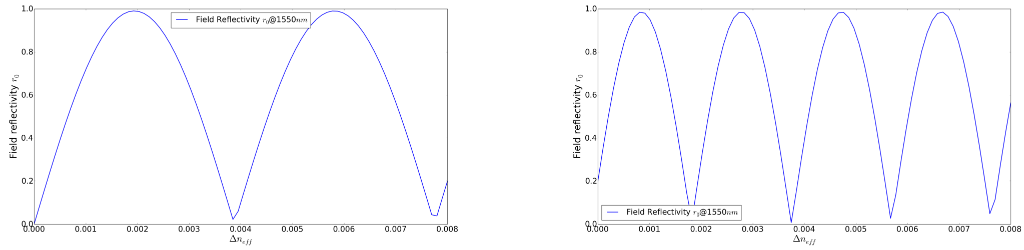
$$\Delta\lambda = \frac{\lambda_1 \lambda_2}{\lambda_0^2} \frac{FSR}{\pi} r_0 \quad (2)$$

Where λ_0 is the original resonance wavelength, λ_1, λ_2 are the two wavelengths when the original resonance becomes split. $\Delta\lambda$ is the split distance between λ_1 and λ_2, and FSR the free spectral range in the wavelength domain. All of the parameters in equation (2) can be extracted from the measured spectra by proper fitting [6], as illustrated in Fig.5a. In terms of the MZI based reflector shown in Fig. 1, one arm L_1 is exposed to the sensing environment while the rest of the device is covered by proper cladding. A small change in the index of the sensing arm can already introduce a significant effect in the reflection of the reflector. It is this sensitivity which we use to create a sensor. Thus the change in environment index will lead to a change in effective index n_{eff} of arm L_1, and a change in reflectivity, and as a consequence a change in the ring peak splitting $\Delta\lambda$.

Characterization and simulation

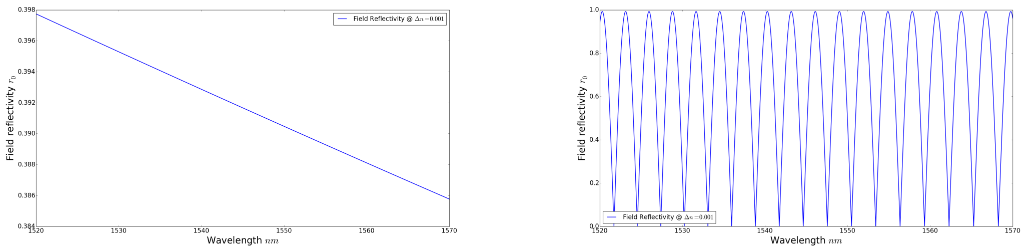
$$\frac{d\Delta\lambda}{dn_{eff}} = \frac{FSR}{\pi} \frac{dr_0}{dn_{eff}} \quad (3)$$

The sensing efficiency is given in equation (3). Clearly, in order to achieve a large efficiency, we need a large FSR and a high sensitivity of reflectivity $\frac{dr_0}{dn}$. The first term is inversely proportional to ring's length L (including the total length of the reflector), while the second term is proportional to the length of MZI's arm L_1 as illustrated in Fig. 2. In



(a) (b)

Figure 2: Field reflectivity r_0 as a function of index change. (a) $L_1 = L_2 = 200\mu m$ (b) $L_1 = L_2 = 400\mu m$



(a) (b)

Figure 3: Field reflectivity r_0 as a function of wavelength. (a) $\Delta L = 0$ (b) $\Delta L = 100\mu m$

summary, the sensing efficiency as a function of sensing length L_1 is relative constant at a value around 350nm/RIU (refractive index unit) as shown in Fig. 4 and Fig. 5b.
Another principle to design the length of MZI is the optical bandwidth of the reflector. On one hand, we want to minimize L_2 in order to get a larger FSR, but on the other hand we want to have a wavelength independent reflectivity. When $L_1 = L_2$, the reflectivity spectrum is flat, but we add the non-functional length L_2 to the roundtrip of the ring. Making L_2 short, while keeping a long L_1 in the sensor arm, will lead to an undesired strong wavelength dependency of reflectivity, as shown in Fig. 3. For the remainder of this paper we work with a flat reflection spectrum, and we choose $L_2 = L_1$.

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta n_{eff}}{n_{eff}}, \Delta n_{eff} = 1.8 \times 10^{-4} \Delta T \tag{4}$$

Conclusion

In conclusion, we propose a novel structure for sensing application. It consists of a ring resonator with an MZI based reflector inside to introduce peak splitting. The distance between the split peaks could be tracked to sense the index change of the sensing environment. The simulation shows that it has a efficiency of 350nm per RIU, and that the sensor is less sensitive to temperature drift.

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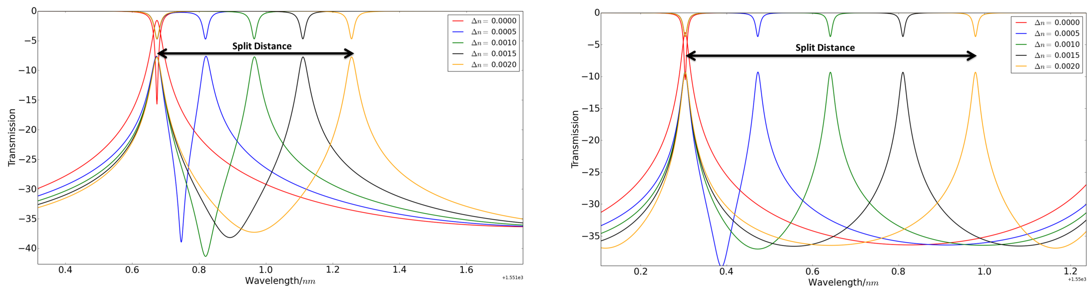
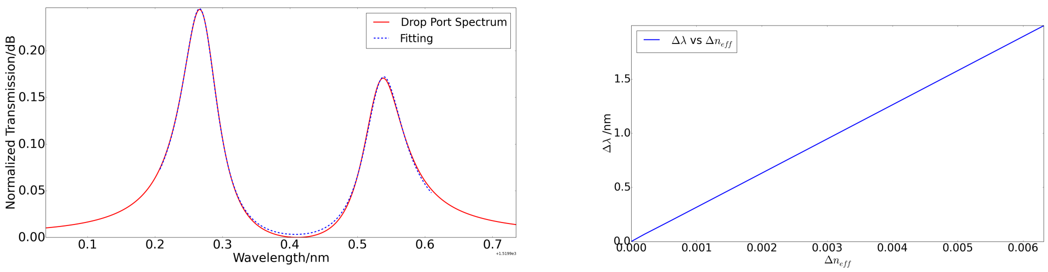


(a) (b)

Figure 4: Simulated spectra of two devices, (a) $L_1 = L_2 = 100\mu m$. (b)$L_1 = L_2 = 250\mu m$. The red curve shows the original non-split resonance, while other colorful curves indicate how the split distance increases with increasing index change of the sensing arm. The result shows a efficiency around 350 nm/RIU.



(a) (b)

Figure 5: (a)Fitting with our model. The simulated circuit includes some inevitable parasitics or nonidealities, for instance the backscattering, parasitic reflections at interfaces, imperfections of the directional couplers etc. (b)$\Delta\lambda$ as a function of Δn_{eff}.

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