Novel optical sensor based on the silicon crossing-coupled microring resonator

Huaxiang Yi,1 Qifeng Long,1 Xingjun Wang1 and Zhiping Zhou,1,2,*

1State Key Laboratory on Advanced Optical Communication Systems and Networks, Peking University, Beijing, 100871, China
2School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, 30318, USA
zjzhou@pku.edu.cn

Abstract: A fabrication friendly crossing-coupled microring resonator was utilized to construct a compact and robust optical sensor which demonstrated a high sensitivity of 225nm/RIU experimentally.

Introduction
Microring resonators (MR) can be realized in an ultra-compact scale and exhibit highly wavelength selective resonances [1]. The compactness of MRs makes them useful for sensing application [2]. The weak coupling between MRs and waveguides is required to maintain the resonances. Typically, controlling the gap between the MR and straight waveguide is the most useful way to adjust the coupling coefficient; however, a gap of < 200 nm for Si MRs is desirable, which presents fabric ation difficulties. Racetrack MRs provide one way to alleviate the problem [3]. The length of the coupling region is then designed to obtain the appropriate coupling. These MRs are sensitive to the gap size between MR and straight waveguide. In addition, the multimode-interference (MMI)-coupled MR has been proposed to solve the problem [4]. However, the MMI coupler suffers from the large size. In this paper, we propose and experimentally demonstrate a novel crossing-coupled MR (CMR) configuration for optical sensing applications.

Theory
A CMR having a straight waveguide crossing an MR is shown in Fig. 1(a). The input light from the straight waveguide is coupled into the ring cavity at the crossings. The CMR actually exploits the intrinsic crosstalk to serve as a coupler to implement the MR. The forward and backward propagating optical fields at each crossing are defined as in Fig. 1(b). The optical field propagating toward the crossing in arm X is labeled as $E_{X1}$; the optical field propagating away is labeled as $E_{X0}$ (where X = 1,2,3,4 represents the respective arm). In order to analyze the light propagation inside the CMR, coupled-mode theory is applied. The optical field distribution in the entire CMR structure is depicted as in Fig. 1(c).
Fig. 1. (a) Configuration of the CMR, (b) the optical fields in the crossing, (c) model of the CMR.

Assuming the two crossings are identical, the optical fields at the right crossing are

\[
\begin{align*}
E_{40} &= -rE_{11} - kE_{21} - tE_{31} - kE_{41} \\
E_{20} &= -kE_{11} - rE_{21} - kE_{31} - tE_{41} \\
E_{30} &= -tE_{11} - kE_{21} - rE_{31} - kE_{41} \\
E_{40} &= -kE_{11} - tE_{21} - kE_{31} - rE_{41}
\end{align*}
\]

(1)

where \( r \) is the reflection coefficient of the crossing, \( k \) is the coupling coefficient in the perpendicular direction, and \( t \) is the transmission coefficient of the crossing; neglecting scattering loss at the crossing, \( r^2 + 2kt^2 + t^2 = 1 \).

The arms between the two crossings are the two bent waveguides comprising the upper and lower portions of the MR and the straight waveguide passing through the center. Based on the loss and phase change of the propagation through the arms, the following relations relate the fields in the arms at the left and right crossings,

\[
\begin{align*}
E_{21} &= -a \exp(i \cdot \pi \cdot \frac{\pi d}{\lambda})E_{60} \\
E_{31} &= -b \exp(i \cdot 2\pi \cdot \frac{d}{\lambda})E_{50}, \\
E_{41} &= -a \exp(i \cdot \pi \cdot \frac{\pi d}{\lambda})E_{80}
\end{align*}
\]

(2)

where \( a \) is the transmission of one half circle in the bent waveguide (i.e., half the MR), \( b \) is the transmission of the straight waveguide through the center, and the \( d \) is the diameter of the ring cavity. Equation (2) represents unidirectional propagation between the crossings.

**Results and Discussion**

The resonance spectrum of the CMR based on above theoretical model is numerically obtained by setting parameters \( k, r \) and \( t \) equal to 0.18, 0.84 and 0.24 based on the experiment result from the reference [5]. On the other hand, a SOI CMR is fabricated to prove our concept and to demonstrate its application as a sensor. Both theoretically and experimentally obtained spectra are compared in Fig. 2, which shows a good agreement. The spectra are periodic but not uniform. The reason is that the dominant resonance occurs inside the microring cavity, which is superimposed with the Fabry–Perot resonance from the straight waveguide. Therefore, the resulting resonance spectrum shape reflects a multi-resonance-coupling inside the CMR [6].
Different refractive indexes of 1.468, 1.470, 1.472, and 1.478 are applied to test the sensing performance of the CMR. The results are shown in Fig. 3, which indicate a sensitivity as high as 225nm/RIU.

**Conclusion**

A novel silicon crossing-coupled microring resonator is proposed and realized as a compact, highly sensitive optical sensor, which, at the same time, relaxes the fabrication demand through its unique coupling mechanism. The resonance modal is investigated with the coupled mode theory. The experimentally obtained resonance spectrum agrees well with the theatrical result. A compact optical sensor, having its sensitivity as high as 225nm/RIU, is demonstrated experimentally.

**Acknowledgements**

The work is partially supported by the National Natural Science Foundation of China by Grant Nos. 60578048 and 60977018.

**Reference**