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# Compact SOI optimized slot microring coupled phase-shifted Bragg grating resonator for sensing

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ABSTRACT

We propose a novel sensor structure composed of a slot microring and a phase-shifted sidewall Bragg gratings in a slot waveguide. We first present a theoretical analysis of transmission by using the transfer matrix. Then, the mode-field distributions of transmission spectrum obtained from 3D simulations based on FDTD method demonstrates that our sensor exhibit theoretical sensitivity of 297.13 nm/RIU, a minimum detection limit of $1.1 \times 10^{-4}$RIU, the maximum extinction ratio of 20 dB, the quality factor of $2 \times 10^{3}$ and a compact dimension-theoretical structure of 15 μm × 8.5 μm. Finally, the sensor's performance is simulated for NaCl solution.


## 1. Introduction

Silicon photonic devices are widely applied in optical communication and sensing, including ultrafast passive photonic networks, optical interconnect systems, bio-medicine and environment monitoring [1–3]. Silicon photonic devices can potentially offer through its compatibility with the complementary metal–oxide–semiconductor (CMOS) fabrication processes [4]. The various optical structures have been widely investigated during the past two decades. The increasing interest widely devoted to Silicon on Insulator (SOI) technology, which is one of the most promising choices for sensing applications [5–7]. The high-$Q$ optical microring resonators are one of the essential elements of sensing application [8,9]. However, the resonant wavelength variation exceeds free-spectral-range (FSR) of a microring-resonator filter due to the high-order mode overlaps between cladding and evanescent field [10]. In order to achieve high-$Q$ factor and large measurement range simultaneously, several structures and strategies have been proposed and demonstrated to enhance the sensitivity of microring resonator [11–13]. A microring resonator composed of slot waveguide has been adopted [14,15]. The slot configuration has a better quality factor, and can give a smaller detection limit for optical sensor applications [16–18]. A great variety of optical devices based on the slot waveguide structure have been designed and realized [19–23].

In the past few decades, Bragg gratings has been extensively researched [24], the refractive index (RI) of guide mode is modulated by physically corrugations. Most conventional silicon photonic Bragg gratings are based on strip or rib waveguides, where the electric field is concentrated in the silicon so that weak evanescent field tails are available for the sensing [25]. Sidewall gratings in slot waveguide show that the electric field intensity in low-index region becomes much higher than that in the high-index material [26]. Furthermore, a slot phase-shifted Bragg grating can generate a sharp resonance peak in the transmission spectrum [27]. The waveguide Bragg gratings fabricated on SOI platform have been theoretically analyzed and experimentally demonstrated [28,29]. The SOI micro-ring resonator and waveguide gratings are well-established silicon photonic devices [30–34]. An all-pass microring-Bragg gratings coupled-resonator system has been designed and fabricated to realize a conversion between electromagnetically induced transparency (EIT) transmission and Fano transmission [35,36]. Subsequently, a label-free optical biochemical sensor with a large measurement range based on grating-microring resonator has been proposed and demonstrated [37].

In this paper, we propose a novel sensor structure composed of a high-sensitivity slot microring and a phase-shifted sidewall Bragg gratings in slot waveguide. The paper is organized as follows. In Section 2, the optical field distribution of the cross section of the slot waveguide is derived. In Section 3, the transmission spectrum and the mode field distribution are simulated by using 3D FDTD method, and we evaluate the performance of our sensor with varying NaCl concentrations. Finally, in Section 4, the conclusion are summarized.

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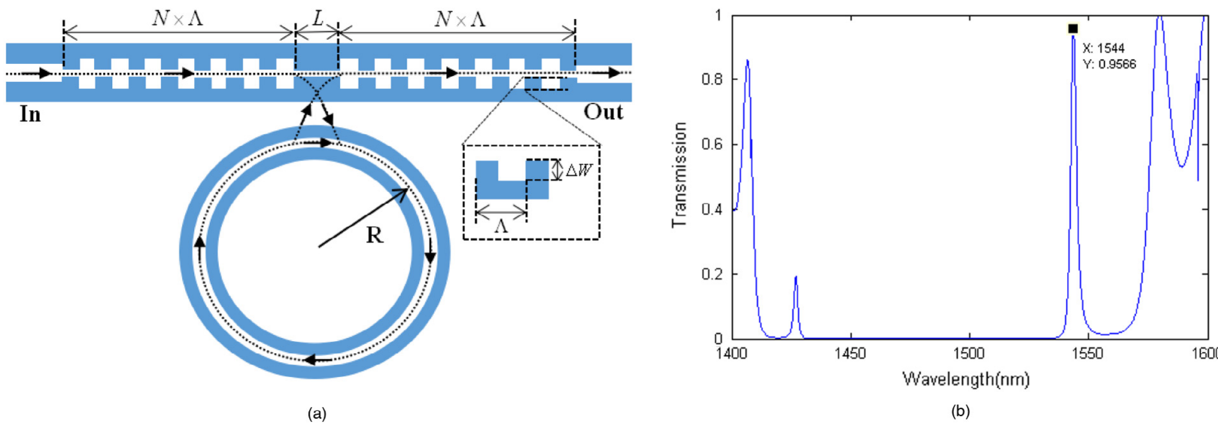


**Fig. 1.** (a) Top view schematic diagram of novel sensor structure composed of a slot microring and a phase-shifted sidewall Bragg gratings in slot waveguides and the arrow indicates the direction of light propagation. (b) The normalized transmission spectrum.

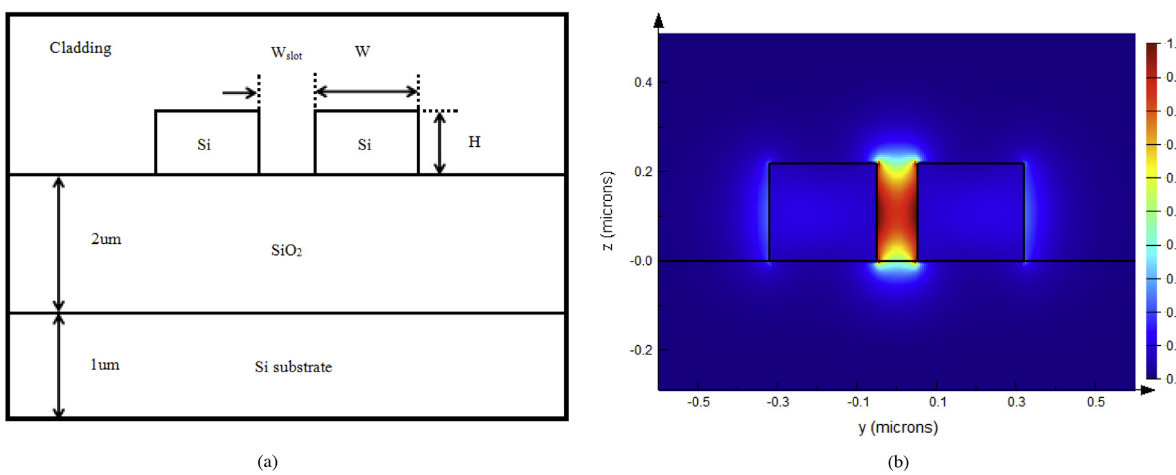


**Fig. 2.** (a) Schematic diagram of the cross section for the slot waveguide based on SOI structure. (b) Cross section and the simulated mode profile for the fundamental quasi-TE mode in MODE Solution.

## 2. Operation principle

As shown in Fig. 1(a), our system consists of a pair of nano-scale slot rectangular waveguide Bragg gratings and a slot microring resonator. When light propagating through the slot rectangular waveguide Bragg gratings, and the effective RI of the guided mode is modulated by corrugations, the weak evanescent field decays, then a stop band appears in the transmission spectrum. The phase-shifted Bragg gratings with sidewall corrugations in slot waveguide is formed by periodically patterned, partially etched rectangular perforations. The optical field of Bragg gratings are coupled into the microring system via their weak evanescent tails. After propagating through one cavity round-trip, the wave couples back into the waveguide Bragg gratings and interferes with the transmitted wave. At resonance, there is destructive interference.

Here, $\Delta W$ denote the perforation depth and $\Lambda$ is the period, $L$ denote the phase-shifted length, $N$ is number of grating periods. Due to the Bragg gratings act as partially reflective elements, the transfer matrix of microring can be expressed in the form [34]

$$T_{ring} = \begin{pmatrix} \dfrac{-\alpha t^* + e^{-j\varphi}}{-\alpha + te^{-j\varphi}} & 0 \\ 0 & \dfrac{-\alpha + te^{-j\varphi}}{-\alpha t^* + e^{-j\varphi}} \end{pmatrix} \quad (1)$$

where $\alpha$ is loss coefficient, $t$ is transmission coefficient. The phase $\varphi = 4\pi^2 n_{eff} R/\lambda$, where $n_{eff}$ is effective RI, $\lambda$ is wavelength, $R$ is radius of microring. According to the transfer matrix, the equation for microring-Bragg gratings based coupling resonate system can be defined as [38]:

$$T_{in} = T_B T_{left} T_{ring} T_{right} T_B T_{out} \quad (2)$$

where $T_{left} = T_{right} = \begin{pmatrix} e^{-j\beta L/2} & 0 \\ 0 & e^{j\beta L/2} \end{pmatrix}$ is the transfer matrix of phase-shifted factor, $\beta = 2\pi n_{eff}/\lambda - j\delta/2$ is the complex propagation constant of phase-shifted waveguide segments and $\delta$ is the propagation loss of waveguide per unit length. $T_B$ is the transfer matrix of uniform Bragg gratings. Based on Eq. (2), the transmission spectrum is plotted in Fig. 1(b), there is a sharp resonance generates in transmission spectrum. In the following simulation analyses, we pay close attention to three parameters: quality factor ($Q = \lambda/\lambda_{FWHM}$) [39], sensitivity ($S = \Delta\lambda/\Delta n_{cladding}$) [40] and the limit of detection (LOD $= \Delta\lambda_{\text{minimum}}/S$) [40].

Fig. 2(a) represents the cross-sectional view of the slot waveguide geometry. We assume slot width $W_{slot}$ to 100 nm, waveguide width $W$ to 270 nm, waveguide height $H$ to 220 nm. The RI of the top silicon layer is $n_{si} = 3.48$ and the RI of the silica buffer layer is $n_{sio_2} = 1.48$. Considering sensing application, the cladding should be in aqueous solution. As shown in Fig. 2(b), the slot configuration provides enhance optical confinement in low index slot regions. This unique characteristic makes the slot waveguide sensitivity higher than that of conventional strip waveguides.

## 3. Simulation and performance analysis

A three-dimensional structure of grating-coupled microring resonator is shown in Fig. 3(a). Fig. 3(b) illustrates the distribution of RI of sensor based on SOI platform.