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Improvement of optical sensing performances of a double-slot-waveguide-based ring resonator sensor on silicon-on-insulator platform

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ABSTRACT

We demonstrate a label-free photonic biosensor with double slots based on micro-ring resonator. The footprint is less than 25 μm × 15 μm. Finite-difference time-domain (FDTD) method is used to analyze the influence of several key parameters on the performance of the double-slots micro-ring resonators. An asymmetric structure is considered for the ring waveguide in order to improve the sensor's bending efficiency. Our numerical analysis shows that the sensitivity of double-slot micro-ring resonator sensor with the radius of 5 μm reaches a value of 708 nm/RIU. The quality factor of 580 and the free spectral range (FSR) of 33 nm are achieved.

1. Introduction

Optical biosensors are widely used in many scenarios [1], such as medical analyses, food quality control, environmental monitoring and so on in modern society. Recently, on-line label-free optical detection method has become more and more attractive in terms of ease of operation and reducing device cost. Various photonics structures have been proposed and developed including Mach–Zehnder interferometer [2], surface plasmon sensors [3], optical fiber sensors [4,5]. Most of the optical biosensors have been realized based on the silicon-on-insulator (SOI) material platform owing to its compatibility to complementary-metal-oxide-semiconductor (CMOS) process and high refractive index contrast, which leads to the large-scale production and integration of photonics device based on standard CMOS microelectronics processes and therefore reduction of the chip cost and size.

Among the optical biosensors, micro-ring resonators (MRRs) [6–10], as one of the most promising device structures, offer compact and high sensitivity by their natural circular optical path [10]. However, the sensitivity of around 70 nm/RIU for typical MRRs is not very high [11]. With the marriage of the idea of slot waveguide [12], the interaction between light and matter is enhanced and accordingly the sensitivity has been increased greatly in recent years. In [13,14] Carlborg and Gylfason fabricated a sensor chip based on slot waveguide with Si_3N_4 and achieved the sensitivity of 240 nm/RIU. Robinson reported a micro-ring resonator based on slot waveguide for gas detection with the sensitivity of 490 nm/RIU [15]. In [16], Kargar proposed a multiple-slot waveguide micro-ring resonator. The bending efficiency was greatly improved by introducing an asymmetric structure, but the sensitivity and other geometry parameters were not considered. In [17], Sun fabricated a multiple-slot waveguides biosensor and obtained the sensitivity of 244 nm/RIU. However, it still suffers large device footprint because of the SU8 material system.

In this paper, the design considerations of a high-sensitivity double-slot-waveguide-based micro-ring resonator sensor on SOI platform are investigated. Because many aspects of the design have not been optimized before, a number of challenges need to be carefully addressed. We study the key requirements in detail in order to achieve excellent sensing performance using finite-difference time-domain (FDTD) method.

2. Device structure

Etching a slot in the middle of the photonic waveguide will cause a strong limitation of the quasi-TE mode in the slot region, which enhances the interaction between light and matter and can improve the device sensitivity. Our optical biosensor is based on the novel slot waveguide consisting of a slot and two silicon ribs as shown in Fig. 1(a). In order to obtain a high sensitivity, we increase the electric intensity in the slot region and ensure that the biological molecules can easily enter the slot region. Therefore, the slot

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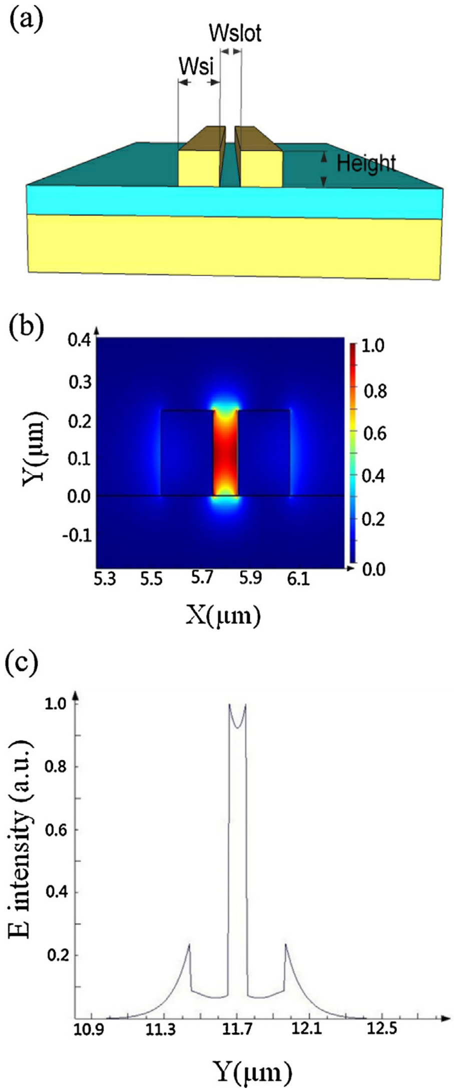


Fig. 1. (a) Structure of the slot waveguide based on SOI; (b) the power profiles of the cross section of the slot waveguide; (c) the electric intensity of the slot waveguide.

region cannot be neither too wide, which will weaken the electric intensity in the slot region, nor too narrow, which will stop the molecules from entering the slot region. Fig. 1(a) shows the optimized structure of this waveguide. The slot height and width are 220 nm and 100 nm, respectively. The silicon rib width W_{si} is 210 nm. The energy ratio of the slot region reaches 30% and an extremely strong limitation of the electric field is achieved. Fig. 1(b) and (c) shows the power profile and electric intensity of the slot waveguide indicating a strong electric intensity confinement in the slot region.

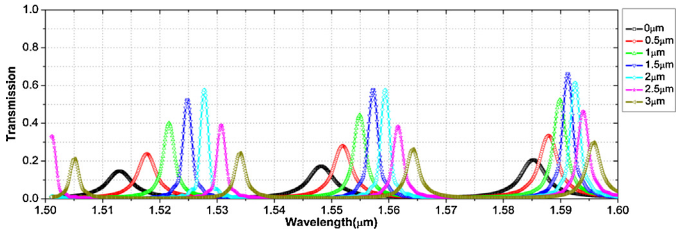


Fig. 3. The transmission spectra of the ring resonator as a function of coupling length L_c.

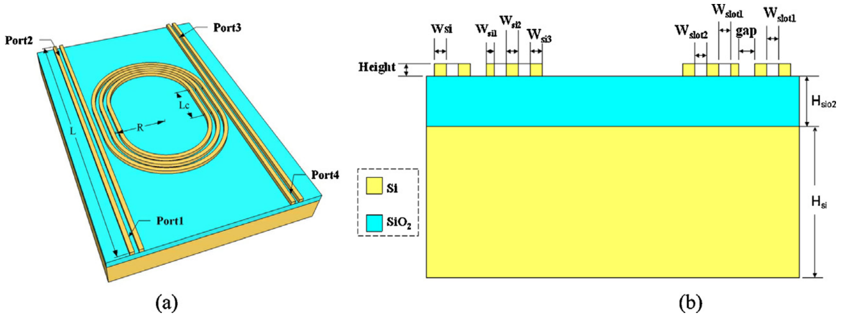
Fig. 2(a) and (b) is the three-dimensional and cross section structures of the double-slot micro-ring resonator, respectively. Two narrow slots are etched in the micro-ring resonator. A vast fraction of the quasi-TE mode will concentrate in the slot region. An asymmetric structure is considered for the ring resonator to improve the sensor's bending efficiency. The ring resonator also has one input and one output waveguides, each with a single slot etched in the middle. When light enters from the left straight waveguide from Port 1, it will be coupled into the micro-ring resonator and then coupled out to Port 4 through the right straight waveguide if the resonance condition is satisfied, or it will be directly dropped out from Port 2 if the resonance condition is not satisfied. The bio-liquid or gas to be probed will be flowed over the top of the sensor.

3. Simulation results

In order to obtain higher quality factor and sensitivity, finite-difference time-domain (FDTD) method is used to optimize the sensing performance of this double-slot-waveguide-based micro-ring resonator sensor. We consider several key parameters including the coupling length L_c, the coupling spacing *gap* (minimum spacing between the input straight waveguide and micro-ring waveguide), the outer Si rib width W_{si1}, the middle Si rib width W_{si2}, the inner Si rib width W_{si3}, the slot asymmetric coefficient of the micro-ring A (the ratio of W_{si2} over W_{si23}), inner slot width of the micro-ring W_{slot2}. W_{si23} is the sum of the middle Si rib width W_{si2} and the inner Si rib width W_{si3}.

3.1. Optimization of the coupling length L_c

Fig. 3 shows transmission spectra of the double-slot micro-ring resonator with different coupling length L_c. The maximum output power increases as L_c increases from 0 μm to 1.5 μm, but then decreases as L_c increases from 2 μm to 3 μm. When L_c equals to 1.5 μm or 2 μm, output power reaches its maximum and quality factor is high. Therefore, the value of coupling length L_c is set to 1.5 μm considering the requirement of small device footprint.



(a) (b)

Fig. 2. (a) Three-dimensional structure and (b) cross section structure of double-slot micro-ring resonator.