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# Double-Slot Optical Ring Resonator Sensor

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**ABSTRACT:** Optical micro-ring resonator (MRR) sensors are an emerging technology that attracts attention not only because it's small footprint but also because of its high-quality features. In this work, a Silicon on Insulator (SOI)-based MRR sensor is studied for a practical label-free sensor. After the analysis of this study, it is found that a smaller (compare to previous studies) label-free optical sensor with a sensitivity of 206nm/RIU and a q-factor of 17900 can be obtained when the optimal designed parameters are used. Thus, it is believed that, this work would shed a light on optical sensor technology for more compact-efficient, low-cost and complementary metal-oxide-semiconductor (CMOS)-compatible sensors for daily life usage.

**Keywords:** Optic Sensor, Double-slot, Micro-ring resonator,

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## INTRODUCTION

Optic Devices based on silicon micro-ring resonators have a vast potential for integrated photonic circuit (PIC) technology. Micro-rings are the key element for a wide range of applications such as optical sensing (Zang et al., 2015; Washburn et al., 2010), optical filtering (Yanming et al., 2012), lasers (Yao et al., 2011), food quality control, environmental monitoring and so on (Fan et al., 2008). Among all these applications, optical sensing has become more attractive in terms of small footprint, sensitive detection potential, ease of operation and reducing device cost. Due to the compatibility of insulated silicon (SOI) platforms with complementary metal oxide semiconductor (CMOS) technology, the majority of optical sensors are implemented on SOI.

SOI-based MRR sensors exhibit small footprint and ultra-sensitive detection potential owing to their high-quality factor (q-factor) characteristics. With the utilization of these structures a quality factor as high as $10^5$ can be achieved employing a device size around 12µm (Cai et al., 2015). In addition, due to MRR sensors' small-structure size, they require less amount of analyte to analyze. The detection mechanism of MRR sensing operations is based on evanescent field interaction with the sensing environment. In case of an intrusion of analytes on the MRR, the resonance state of the resonator changes, causing a resonance wavelength shift (Cicek et al., 2017) or an intensity change (Cicek, 2018). In this way, the analytes can be detected with high accuracy by detecting either the shift of resonance peak or its intensity change. In order to increase the sensitivity, different geometries have been utilized (Yuan et al., 2014; De Vos et al., 2017). Among them, employing a double-slot geometry it is possible to obtain a sensitivity of as high as 560 nm/RIU, as well as a quality factor of 1020 with the footprint of less than 13µm X 13µm (Gu et al., 2019). Even though slot-sensors offer high sensitivity, they experience high optical losses that directly affect the quality factor (Steglich et al., 2019).

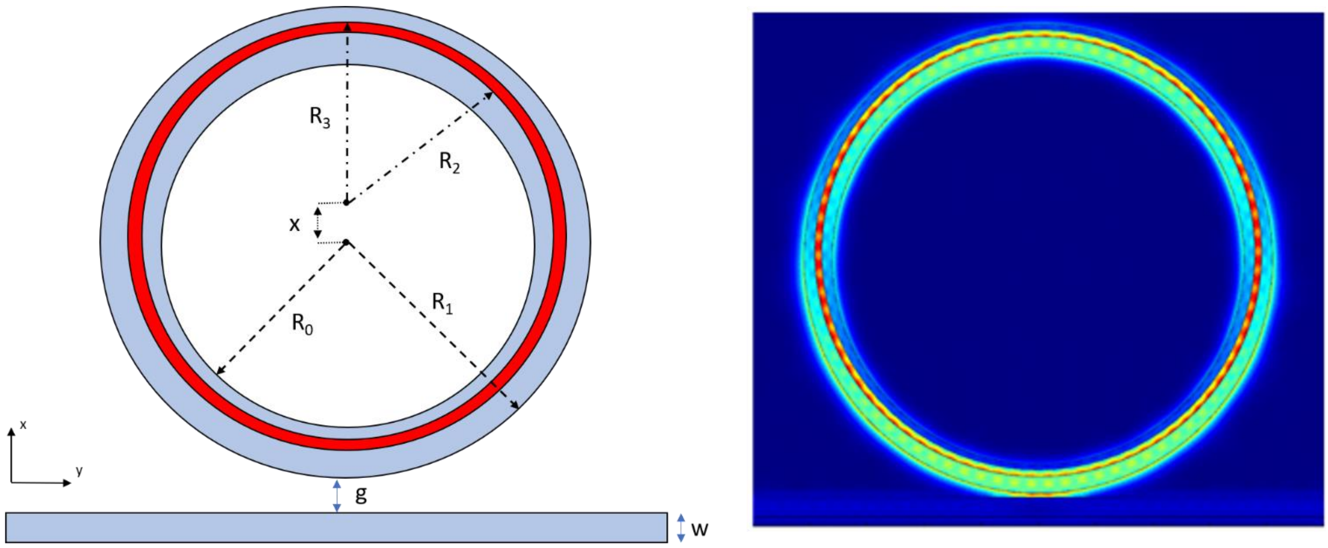
In this study, a new geometry is presented for the purpose of higher q-factor sensing and for smaller-footprint with a reasonable sensitivity compare to previous studies. Based on this condition, an SOI-based MRR coupled to a straight waveguide structure is proposed and studied numerically. As the sensing layer, a ring is placed asymmetrically in the cavity waveguide in such a way that it would not interfere the coupling efficiency. The resonance wavelengths of whispering gallery modes (WGMs) are examined in terms of q-factor, sensitivity and footprint for different refractive index of slot-ring and results are discussed here.

## MATERIALS AND METHODS

### The Sensing Geometry and the Numerical Method

The system schematic is presented in Figure 1-a. It consists of a straight waveguide coupled to a conventional double-slot micro-ring resonator (cavity waveguide) on the SOI platform. The silicon MRR has an inner and outer radius of $R_0$=3.6µm and $R_1$=4.1µm, respectively. The silicon straight waveguide, on the other hand, has a width of w and a fixed length of 10µm. The coupling gap between the straight and the cavity waveguide is set to be g= 70nm.

In addition, a slot-ring filled with sensing element is placed asymmetrically in the cavity waveguide as the detection part, shown in Figure 1-(a-b). The slot-ring has inner and outer radius of $R_2$= 3.79µm and $R_3$= 3.91µm, respectively. As can be seen from the Figure 1b, the traveling mode in MRR system is mostly confined in slot-ring region. Thus, it is expected that the result of interaction between analyte and the sensing part would be more sensitive.




(a) (b)

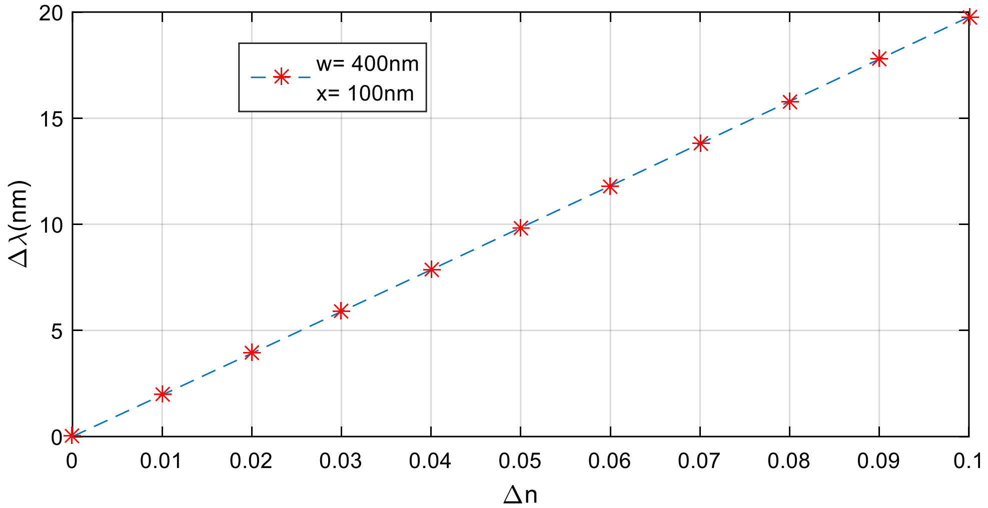
**Figure.1**. (a) The basic structure of MRR sensor and (b) Mode field distribution of the sensor.

In case of an MRR resonator system, to achieve maximum coupling efficiency, both the straight waveguide and the cavity waveguide needs to be comparable in width. However, in this proposed sensor geometry the slot-ring is placed in the MRR resonator reducing the width of cavity waveguide and most definitely reduces the coupling efficiency. In order to overcome this issue, the center of slot-ring is altered away from the MRR resonator with a length of x in the x-direction as shown in the Figure 1-a. This way, the width of the MRR resonator can be increased in the coupling region gives rise to more electromagnetic field pass through the straight waveguide to the cavity.

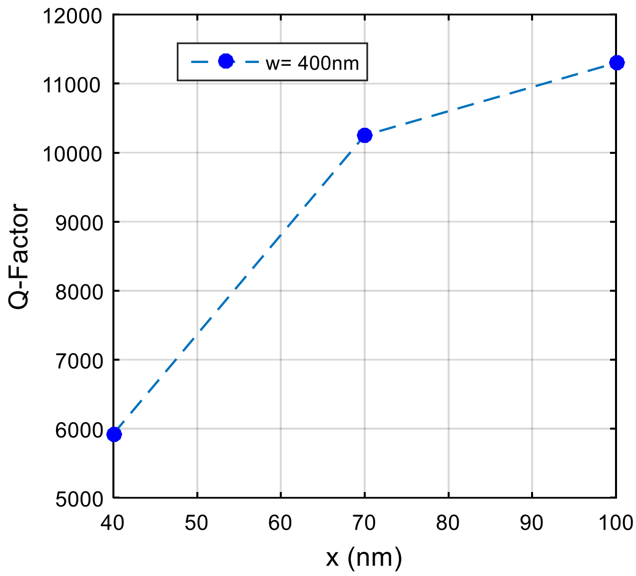
In this paper, COMSOL, a cross-platform finite element analysis (FEM) solver and multi-physics computer software is utilized for 2D numerical simulations. Due to the lack of high-power computational facilities, 2D model is performed. Even though a 3D model is required for a complete understanding of the operation, 2D models also provides sufficient insight about the structure. A quasi-transverse electric (TE) mode Gaussian-beam is launched into the straight waveguide and coupled into the cavity waveguide through the coupling region. The coupled source beam generates whispering gallery modes (WGM) of cavity waveguide and travel around the resonator. In the meantime, the WGMs interact with the slot-ring that is filled with the sensing material. The operation principle of the sensor is based on the WGMs resonances position in the frequency spectrum depending on the slot-ring refractive index. In case of any change in refractive index of the slot-ring, the position of WGMs in frequency spectrum will change. With the analysis of these changes, any changes in the sensing environment can be detected.

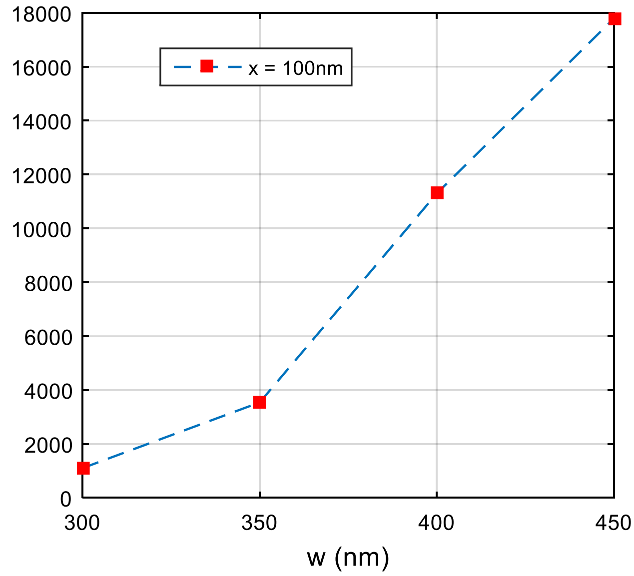
## RESULT AND DISCUSSION

It is well known that in most applications, single mode operation is favorable in terms of loss, size, efficiency and simplicity of the system behavior. Therefore, in this study, the straight and cavity waveguide sizes are determined in such a way that they only support the single mode operation. The proposed sensor structure is investigated with the assistance of Comsol Multiphysics software package. The analysis is made on 2D cross-section of the geometry with the assumption of constant profile and properties throughout third dimension of the sensor.




(a)




(b) (c)

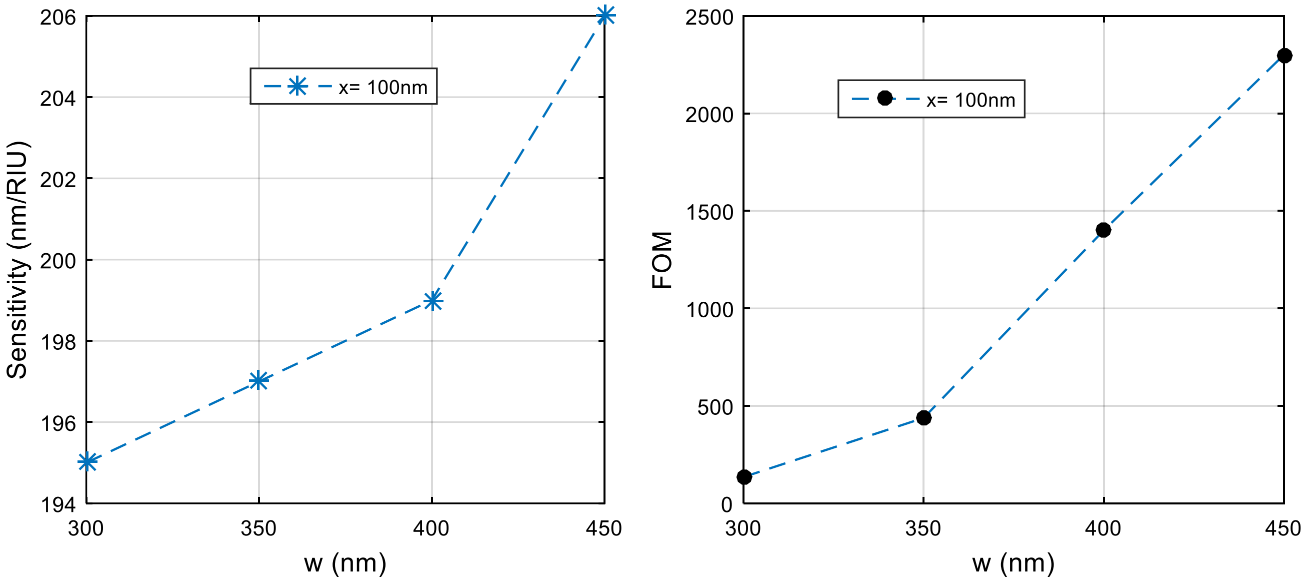
**Figure.2**. q-factor is calculated for a range of (a) x and (b) w values.

The waveguide perturbation theory explains that in the event of a refractive index change in the propagation medium of a mode, the amount of power available in this particular part also changes. (Melman, 1984). This refractive index and the power change alter the resonance frequency of the mode. Considering the proposed sensor structure, any change in refractive index of slot-ring shifts the resonance frequency which establishes the operation principle of the sensing. In Figure 2-a, the resonance wavelength spectrum is depicted in response to refractive index changes of slot-ring, where a structure of w=400nm and x=100nm is used. It is observed that when the MRR undergoes a refractive index changes, it experiences a resonance shift that is directly proportional to the refractive index change. Under these circumstances, a refractive index change of 0.1 creates a shift of 20nm in MRR sensor. In addition to this, the model performance investigation is proceeded with the analysis of the q-factors of the double-slot MRR sensor with various lengths of slot-ring center shifts (x) and straight waveguide width (w), as shown in Figure 2-(b-c). The Q-factor is considered important criteria for sensitivity of the sensor which is determined as the minimal detectable frequency change and is affected by optical losses within the MRR sensor. The q-factor is expressed as the ration of the resonance wavelength exists in

MRR resonator to the full width at half maximum of this resonance as given in Equation 1. Based on this equation the q-factor of the proposed sensor is calculated for a range of x and w values.

$$Q - factor = \frac{\lambda_{resonance}}{FWHM} \quad (1)$$

As can be seen from the Figure 2-b, the quality factor of a double-slot MRR resonator, which contains a slot-ring whose center is 40nm away from its own center is calculated to be 6000 with a w=400nm wide straight waveguide. By keeping the straight waveguide width constant, the q-factor of the resonator increases up to 11000 as the slot-ring resonator center moves 100nm away from the MRR center.




(a) (b)

**Figure.3**. calculated (a) sensitivity and (b) FOM of the double-slot MRR sensor.

This time, employing a slot-ring with a constant center shift of x=100nm, the q-factor of MRR resonator also calculated varying the straight waveguide width. As seen from the Figure 2-c, a q-factor of 1100 can be achieved when a 300nm wide waveguide is used. The figure clearly indicates that as the straight waveguide gets wider, the q-factor increases exponentially. Coupling the light from w=450nm wide straight waveguide to the MRR resonator a q-factor of as high as 17900 is observed. It should be noted that although this value is much higher than previous study (Gu et al., 2019), this can be a guideline for future studies to model the sensor with the optimal values.

The model investigation is continued with the sensitivity analysis of double-slot MRR sensor for a group of refractive indexes of slot-ring resonator in order to evaluate the performance. It is crucial to evaluate the optical sensor performance indicator of sensitivity. Sensitivity can be understood as a change in the resonance wavelength corresponding to a change in the refractive index of slot-ring. The Equation 2 is exploited for the sensitivity calculations. The sensitivity of the proposed geometry also calculated for four different width values of straight waveguide in case of a slot-ring that center shifted x=100nm away from the MRR.

$$S = \frac{\Delta\lambda}{\Delta n_{Slot-ring}} \quad (2)$$

Observing the Figure 3-a, it is clear that the sensitivity trend in the plot is an exponential increase in response to waveguide width. Such that, a sensitivity of 195 nm/RIU can be obtained when 300nm wide straight waveguide is employed. In addition, the sensitivity is increases up to 206nm/RIU with a straight waveguide of w=450nm. Another criterion that is characterizing the performance of the sensor is Figure of Merit (FOM). The value of FOM indicates how much a sensor fits the expectation of the performance, stability and practicality.

$$FOM = \frac{S}{FWHM} \qquad (3)$$

The FOM of the MRR sensor is calculated based on the numerical outcome of the study. The FOM is defined as the ratio between sensitivity and FWHM of the resonance wavelength peak as presented in the Equation 3. As the definition of FOM reveals, improving sensitivity or q-factor of the resonator enables FOM improvement which means the higher the sensitivity and q-factor better the FOM. Exploiting the equation 3, FOM is calculated and presented in Figure 3-b. When calculating the FOM value of the sensor structure, different straight waveguide widths are used to observe the effect of the width on FOM value as well. As the Figure 3-b outlines, the plot of FOM exhibits an exponential-like orientation. From an MRR resonator sensor, employs a slot-ring with shift distance of the center x=100nm, excited by 300nm wide straight waveguide, an FOM value of 135 can be obtained. As the width of the straight waveguide increases up to 450nm, the FOM also increases and reaches a value of as high as 2300. It should be noted that a detailed investigation of all structural parameters is needed for the sake of optimal sensor geometry, since all performance evaluations in this study strongly demonstrate the significant effect of structural parameters, particularly x and w.

## CONCLUSIONS

SOI-based optical slot-structured MRR sensors offer a great hope in sensor technology not only because their high sensitivity and precision features but also their small footprint as well as compatibility with CMOS technology. In this study, a double-slot MRR sensor is studied numerically and results are discussed. According to the outcome of the study, it is obvious to say that, the proposed geometry reduces the optical loss that increases the q-factor of the sensor. In addition, compared to the previous study, not only the q-factor is higher but also the footprint is also reduced which is also a crucial feature in sensor technology. Even if the highest sensitivity of the proposed sensor is observed to be 206nm/RIU, it holds high potential for more efficient and precise optical detection due to the high q-factor of 17900 and less footprint of 10μm X 10μm characteristics of the sensor.

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