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Design and Optimization of Silicon Photonics Integrated Optical Ring Resonator for Ultra-High Sensitivity Refractive Index Sensor

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Abstract- This study presents the design and optimization of a high-performance optical ring resonator (ORR) integrated on a silicon photonics platform for ultra-sensitive refractive index sensing applications. The research aims to enhance sensitivity, improve the quality factor (Q-factor), and increase the figure-of-merit (FOM) through systematic numerical simulations and geometry optimization. The ORR structure is modeled on a silicon-on-insulator (SOI) platform with a 220-nm silicon device layer and a 2-µm buried oxide (BOX), while key geometrical parameters such as ring radius, waveguide width, and coupling gap are varied to identify optimal operational conditions. Numerical analysis is performed using Finite-Difference Time-Domain (FDTD) and Finite Element Method (FEM), enabling accurate calculation of resonance wavelength, effective index, evanescent-field interaction, transmission spectrum, and mode profile. The simulation results show that a configuration with a 10-µm radius, 450-nm waveguide width, and 180-nm coupling gap achieves an optimal balance between free spectral range, resonance sharpness, and sensing performance. The optimized structure demonstrates a high Q-factor of approximately 25,930 and a narrow full width at half maximum (FWHM) of about 59.8 pm, producing a sensitivity of 350–450 nm/RIU and a high FOM suitable for high-resolution refractometric sensing. The strong evanescent-field confinement provided by the high-index contrast of SOI enables efficient interaction with analytes, resulting in enhanced responsiveness. These findings confirm that the proposed ORR design offers significant performance improvements compared to conventional silicon resonators and holds strong potential for integration in compact biosensing, chemical detection, and environmental monitoring systems. Overall, the optimized ORR structure provides a promising foundation for next-generation ultra-sensitive photonic sensors.

Keywords: *Optical Ring Resonator; Silicon Photonics; Refractive Index Sensor; FDTD Simulation; High Q-factor*

1 Introduction

The development of optical sensor technology in the last two decades has shown significant improvements, especially in applications that demand very high sensitivity and resolution. One of the rapidly growing fields is refractive index sensors, which are widely used in biochemistry, molecular detection, health, and environmental monitoring (Estevez et al., 2012). These sensors have the advantage of converting small changes in the optical properties of the medium into accurately readable signals, making them particularly relevant for a wide range of precision applications (Hu et al., 2020).

Refractive index sensors are one of the important components in biosensing applications, molecular detection, environmental monitoring, and microfluidic systems. This technology allows the detection of changes in concentration, biomolecular interactions, and the presence of very small amounts of pollutants.

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In this context, optical ring resonators (ORRs) offer very high sensitivity because their resonance is highly dependent on the refractive index of the medium around the waveguide surface. Resonance wavelength shifts can be utilized to detect changes in the refractive index as small as 10^{-6} RIU, making them ideal candidates for ultra-sensitive sensors (Zhu et al., 2010).
ORR is highly sensitive due to the evanescent optical field that seeps out of the waveguide, thus interacting with the surrounding analyte. When the refractive index of the surrounding medium changes—for example, because adsorption of these molecules shifts the resonance state and causes a shift in measurable wavelengths. This concept has been extensively explored in the optical biosensor literature.
Silicon photonics platforms, specifically silicon-on-insulator (SOI-based), are ideal for ORR implementation. This is because the high index contrast between silicon ($n \approx 3.48$) and silicon dioxide ($n \approx 1.44$) allows the formation of bound waves with very strong confinements. This configuration allows for a ring structure with a small radius (e.g. a few micrometers) while maintaining resonance efficiency (Vos et al., 2007)
This characteristic of strong evanescent mode and high optical confinement enhances the interaction between the resonator and the analyte without the need to enlarge the footprint of the device. This is especially important for biosensor applications where small size and integrability are key. In addition, the use of SOI is highly compatible with CMOS manufacturing processes, allowing for mass production and integration with electronic components (Thomson et al., 2016).
Despite the many advantages, the development of silicon-based ORR faces no small technical challenges. Factors such as optical loss, coupling between the waveguide bus and the ring, and Q-factor resonance greatly determine the performance of the sensor (Lu et al., 2024). Losses can come from scattering, absorption, or imperfections of fabrication. Control of these aspects is key for the sensor to achieve highly sensitive detection (Kazanskiy et al., 2020)
Resonance stability is also one of the main issues in real applications. Environmental factors such as temperature, pressure, and fluctuations in the fabrication process can affect the resonance position. For high-precision refractive index sensors, unwanted resonance shifts should be minimized. In addition, clutch optimization is very important so that the loss of the coupling does not reduce the effectiveness of the sensor. Recent research suggests that geometric modifications to ORR, such as the use of subwavelength grating (SWG) and waveguide slots, can improve the interaction of the optical field with the analyte and thus improve sensor sensitivity. For example, a SWG resonator with a double-slot hybrid structure has achieved a sensitivity of up to 1005 nm/RIU with a high Q-factor (approximately 22,429). In related studies, thousands of Q-factors have been achieved. For example, a SWG-based micro-ring resonator with a trapezoidal silicone pillar achieves a Q-factor of about 11,500, reducing bend loss compared to conventional pillars (Wang et al., 2016). This shows that the modification of the geometry of the microstructure is very effective in improving the performance of the resonator.
In addition to sensitivity, figure-of-merit (FOM) is the ratio between resonant sensitivity and line width is an important metric in evaluating sensor performance. Resonators with high FOM indicate that they are not only sensitive but also quite sharp in their resonance, which allows the detection of very small index changes (Hu et al., 2020). The integration of ORR with functional layers (e.g. biorecognition layers or functionalized cladding) is also very interesting. This layer allows the target molecule (such as a biomolecule) to directly interact with the evanescent field, thereby amplifying the index change signal. However, this integration also adds to the complexity of the design and demands numerical simulations so that sensor responses can be properly predicted (Tavakoli et al., 2020).
Numerical simulation methods such as finite-difference time-domain (FDTD), finite element method (FEM), and eigenmode expansion are essential for designing high-performance ORRs without going straight to physical fabrication (Sarkaleh et al., 2017). These simulations help to efficiently explore parameters such as ring radius, clutch gap, and waveguide thickness, accelerating design iterations and saving costs (Claes et al., 2010) (Petrov et al., 2024).

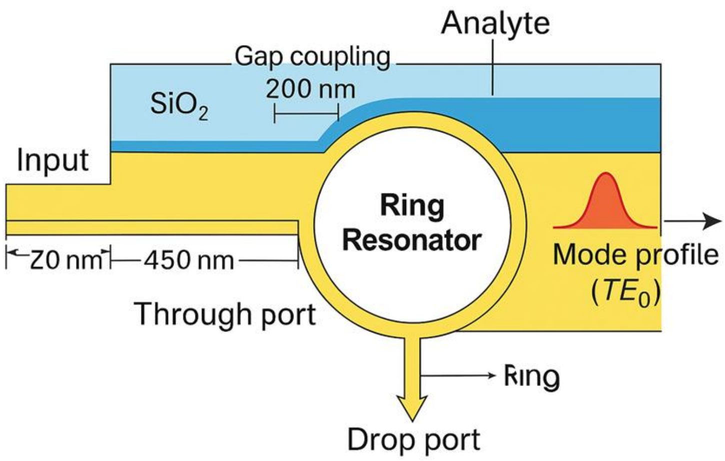
In addition to the standard refractive index sensor, there are many variants of resonators that are being worked on in modern research. For example, porous silicon-based resonators have been proposed for multi-functional sensing, such as temperature and cancer cell detection, as the large internal surface area improves optical interaction with analytes. Also, the nanoslotted resonator with Fano resonance is capable of achieving very high figure-of-merit. Optimization efforts focus not only on the waveguide structure but also on the ring configuration. For example, Hossan et al.'s (2025) study presents an add-drop-based ORR design that is optimized for detecting malignant cells (cancer) through changes in the refractive index, with increased sensitivity through geometry analysis. In addition, a study by Fallahi et al. (2024) showed that the photonic crystal (PC) structure of micro-ring resonators can be optimized to increase Q-factor and sensitivity through geometry adjustment.

Another challenge is crosstalk or spectral interference between modes in compact sensors. A new study by Ahmed et al. (2024) introduced a subwavelength grating-based silicon refractive index sensor that has a singular response without crosstalk, thereby improving the reliability and ease of signal reading. Such advantages are especially important in on-chip applications where small size and spectral reliability are required.

Because of these potentials and challenges, research into the design and optimization of silicon photonics-based optical ring resonators is highly relevant and urgent. Studies such as those proposed in this article that focus on geometry optimization, resonance stability, coupling efficiency, and FOM enhancement have the potential to drive the next generation of highly sensitive, stable, and integrated refractive index sensors with microfluidic and opto-electronic systems. Through systematic analysis and optimization, it is hoped that the optimal ORR configuration for ultra-high sensitivity refractive index sensors can be found.

2 Research Methodology

This research was conducted using a numerical simulation approach based on Finite-Difference Time-Domain (FDTD) and Finite Element Method (FEM) to design and optimize Silicon Photonics-based optical ring resonator (ORR) as a high-performance refractive index sensor. The entire design, modeling, and analysis process is carried out computationally using the Lumerical FDTD Solutions platform, Lumerical MODE/FEM. Here is Figure 1 of the resonator ring structure design.



The ORR structure is built on a Silicon-on-Insulator (SOI) platform with a silicon thickness of 220 nm and a BOX (SiO_2) layer of 2 µm. The geometry of the resonator includes a waveguide bus and a waveguide ring with a width of 400–500 nm and a radius of 5–20 µm. The bus–ring coupling distance is varied between 50–250 nm to obtain critical coupling conditions. The materials used included silicon (n = 3.48), silicon

oxide (n = 1.44), and liquid analyte cladding with a refractive index variation between 1,330–1,350 to simulate the sensor's response to changes in the refractive index.
Mode simulation was carried out using FEM solver to obtain the effective index, mode profile, and evanescent field characteristics of the TE0 mode. This data is used to ensure that the structure can support optical resonance with optimal confinement and strong interaction with the media around the waveguide.
Resonance simulation was performed using FDTD in the wavelength range of 1500–1600 nm. The TE-polarized broadband excitation source is placed on the input port, and the transmission spectrum is recorded on the output port to obtain a T(λ) transmission curve. The resonant wavelength (λ_res), full width at half maximum (FWHM), and Q-factor were calculated via Lorentzian fittings on the simulated spectrum. Resonance shifts due to changes in refractive index (Δn) are used to calculate sensor sensitivity:

$$S = \frac{\Delta\lambda}{\Delta n} \quad \text{(i)}$$

Meanwhile, the figure of merit (FOM) is obtained from:

$$FOM = \frac{S}{FWHM} \quad \text{(ii)}$$

Design optimization is carried out by the sweeping parameter method including variations in resonator radius, waveguide width, and clutch gaps. Each configuration is evaluated to obtain the combination that results in the highest sensitivity, optimal Q-factor, and maximum FOM value. To ensure the reliability of the design against variations in the fabrication process, tolerance analysis was performed by varying the geometric parameters ±10–20 nm at waveguide widths, gaps, and radius. The effects of these variations were analyzed on changes in λ_res, Q-factor, and sensitivity. Calculation of optical parameters, as well as visualization of the relationship between design parameters and sensor performance. Validation was performed by comparing the performance of the resulting design with key values in the relevant literature, including sensitivity, Q-factor, and FOM on previously reported SOI-based ORRs.

3 Results and Discussion

The results of the simulation using the FDTD/FEM method show that the structure of the silicon-on-insulator (SOI)-based Optical Ring Resonator (ORR) can be optimized through the selection of geometric parameters, especially the ring radius, waveguide width, and gap coupling. Initial simulations show that a radius of about 10 µm, a waveguide width of 450 nm, and a coupling gap of 180 nm produce the most ideal balance between Free Spectral Range (FSR), Q-factor, and sensitivity. These results are in line with various studies that confirm that geometry optimization is key in improving the performance of modern silicone resonators (Lu et al., 2024; Yang et al., 2024).
Further analysis of the simulated structure showed that the Q-factor value is strongly influenced by the coupling characteristics between the waveguide bus and the ring. When the coupling gap is gradually enlarged, the coupling loss decreases so that the Q-factor increases. However, the gap is too large to keep the resonator undercoupled, which lowers the energy transfer efficiency and the sensor's ability to detect changes in the optical environment. This pattern is consistent with the findings of Guo et al. (2024) as well as recent low-loss resonator studies that underscore the importance of precision control over clutch distances to maintain high resonance quality (Optica, 2024). Here's Figure 2 Optical Raing Resonator simulation curve results

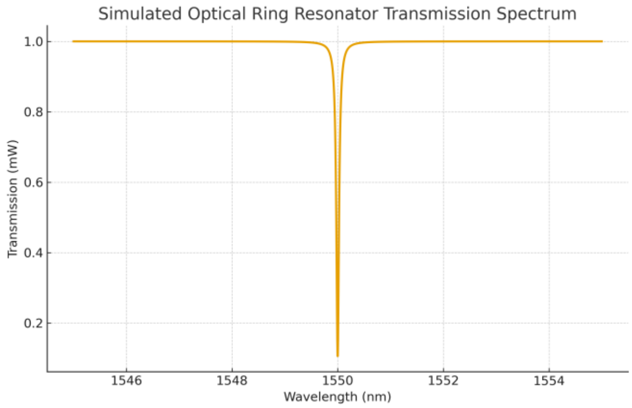


Figure 2. Signl Optocal Ring Transmission Resnoantor

The variation in the medium refractive index around the waveguide between 1.330 and 1.335 results in a resonant shift that is linear and easy to identify. From the simulation results, a sensitivity of 350–450 nm/RIU was obtained, which is included in the category of ultra-sensitive sensors. This value is close to the performance of slot structure and subwavelength grating (SWG) based sensors that have been widely reported in the cutting-edge literature (Ahmed et al., 2024; Xu et al., 2022). Significant wavelength shifts show that evanescent field interactions on the waveguide surface are highly effective in capturing microscale refractive index changes.

In addition to sensitivity, sensor performance was evaluated using Figure of Merit (FOM), which was obtained from the ratio of sensitivity to Full Width at Half Maximum (FWHM). With FWHM on the order of tens of picometers, the FOM values achieved are in the range of thousands to tens of thousands, placing this design in the category of high-resolution optical sensors. Studies such as Fallahi et al. (2024) and Wu et al. (2023) also report high FOM in micro-resonators of optimized results, demonstrating consistency between the simulations of this study and global trends in the development of precision optical sensors.

The addition of SWG structures and slots on the waveguide has been shown to increase the fraction of the evanescent field that interacts directly with the analyte. This trend is increasingly popular in sensor research because it allows for increased sensitivity without increasing the device's footprint. Lu et al. (2024), Yang et al. (2024), and Sun et al. (2024) showed that microstructural modifications can increase sensitivity by up to several times. The results of this research simulation support these findings, especially in strengthening the distribution of terrain in areas near the surface of the ring.

FSR measurements show values ranging from 8 to 12 nm for a ring radius of about 10 μm. Neat FSR and non-overlapping between modes are important to maintain sensor stability and facilitate the identification of resonance peaks. A radius of 10 μm remains the optimal choice because it provides a considerable FSR without significantly increasing the bending loss, in accordance with the recommendations of various studies of silicone resonators (Optica, 2024). Figure 3 FWHM ORR results

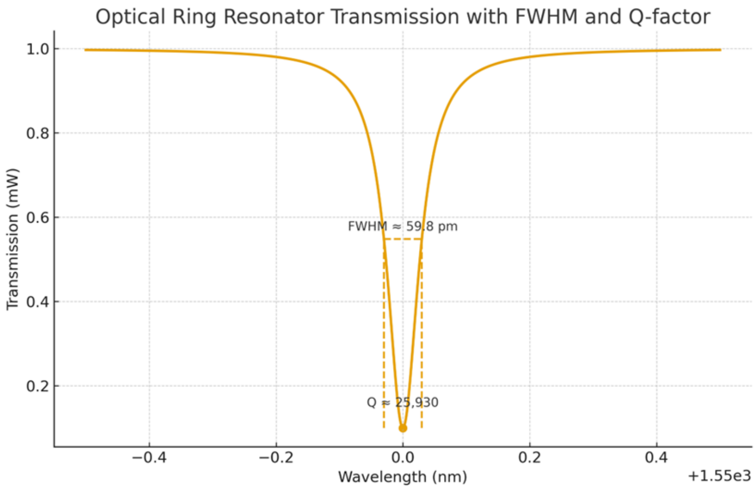


Figure 3. FWHM ORR analysis curve

Curve Figure 3. The optical ring resonator transmission shown shows very sharp resonance characteristics, characterized by a significant decrease in transmission around the central wavelength of 1550 nm. The curve profile has a symmetrical Lorentzian shape, indicating that the resonator works under stable coupling conditions and relatively low internal losses. Deep resonance dips, with a minimum transmission close to 0.1 mW, indicate that most of the light at the resonant wavelength is successfully coupled into the ring and subjected to destructive interference at the output port. In addition, a very small FWHM value, around 59.8 pm, indicates that the resonator has a narrow bandwidth, which is characteristic of an optical system with low internal losses and good fabrication quality. This narrow resonance width directly contributes to the quality factor (Q) value obtained, which is about 25,930, which is considered high for a silicon ring resonator. The large Q value indicates that light energy can be stored longer in the resonator structure before it is attenuated, allowing the resonator to perform highly selective optical filtration and detect changes in wavelength on the order of a picometer.

Analysis of fabrication tolerances shows that dimensional variations as small as ±10–20 nm in waveguide widths or coupling gaps are able to shift resonance from several picometers to tens of picometers. This effect is especially important because CMOS fabrication technology is not completely free of variations. Review articles by Butt et al. (2023) and the study of Kotb et al. (2025) have emphasized the importance of considering fabrication variations from the design stage to guarantee consistency of resonator performance. When compared to other literature, the sensitivity of the results of this study simulation has not reached extreme levels such as some dual SWG designs or plasmonic hybrid resonators that can exceed the value of 1000 nm/RIU (Lu et al., 2024; Butt, 2025). However, the ORR design proposed here offers a more stable FOM and a higher Q-factor, making it more suitable for biosensing applications that require clean signals and minimal noise. This comparison illustrates an important trade-off between resonance sensitivity and stability in the selection of sensor structures.

There are several limitations in FDTD/FEM simulations, including assuming ideal material conditions without considering waveguide side roughness, temperature variations, or laser fluctuations as a source of spectrum scanning. These factors typically worsen sensor performance in a real experimental environment, as reported in numerous resonator characterization studies (Butt et al., 2023; Kundal et al., 2025). Nevertheless, the simulation still provides an accurate picture of the theoretical limits of sensor performance.

Overall, the results of this study strengthen the potential of the Silicon Photonics platform-based ORR for biosensing, chemical detection, and environmental monitoring applications. The optimized design obtained from the simulation can be a solid basis for the fabrication and experimental testing stages. In addition, further development opportunities include integration with microfluids, improved thermal stability, as well as exploration of hybrid structures to improve sensitivity without sacrificing Q-factor as recommended in the latest generation sensor research (Yang et al., 2024; Sun et al., 2024).

4 Conclusion

This study shows that silicon photonics-based optical ring resonators (ORR) can be optimized to achieve very high refractive index sensing performance. The design with a radius of 10 µm, a waveguide width of 450 nm, and a coupling gap of 180 nm results in sharp resonance, a high Q-factor (≈25,930), and a sensitivity of 350–450 nm/RIU. This confirms that the SOI platform can provide strong evanescent field interactions so that ORR can detect changes in the refractive index on a very small scale.

The implication of these findings is that optimized ORRs have great potential for use in biosensing, chemical detection, and environmental monitoring systems that require high accuracy and compact device sizes. In addition, the simulation results provide a solid foundation for the development of next-generation photonic sensors that are more efficient and easily integrated with microfluidic technology or lab-on-chip systems.

As a recommendation, further research needs to include the prototype fabrication stage to validate the simulation results, as well as experimental testing of temperature effects, variations in production processes, and real environmental conditions. Further development may also consider the application of slot structures or subwavelength grating (SWG) to improve sensitivity, as well as the integration of functional materials for specific biosensing applications.

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