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Multi-Objective Optimization of Optical Micro resonators for Integrated Optoelectronic Applications

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Abstract

This study presents the multi-objective design and optimization of optical microresonators for integrated optoelectronic applications. The research addresses key challenges such as enhancing efficiency, minimizing energy losses, and improving structural performance to achieve high-Q operation. Using advanced photonic simulation tools, critical parameters—including doping concentration, geometric modifications, and plasmonic nanoparticle incorporation—were optimized. The results show that a moderately doped MRR (1×10^{17} cm^{-3}) achieves Q-factors exceeding 15,000 and increases the absorption coefficient up to ~1.47, representing more than a sevenfold improvement compared to the undoped case. Furthermore, integration of Au/Ag nanoparticles enhances absorption by nearly 10× and boosts sensitivity by 20–25%. The optimized perforated resonator design also broadens the resonance spectrum, enabling multi-resonant operation suitable for advanced sensing applications. Overall, the proposed hybrid MRR configuration demonstrates superior light confinement, absorption enhancement, and detection sensitivity, highlighting its strong potential for next-generation optoelectronic integration.

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1. INTRODUCTION

Optical micro resonators (MRs) are fundamental components in modern photonic technologies, serving a wide range of industrial and research applications, including high-speed optical communications, signal processing, and precision sensing. Since their inception, MR technology has experienced significant advancements, including improvements in quality factor (Q), device miniaturization, and enhanced light-generation efficiency [1], [2].Among various designs, ring resonators (RRs) are particularly attractive due to their simple geometry, compatibility with silicon photonics, and strong resonance sensitivity to variations in refractive index (RI). Typically constructed from high-index materials such as silicon and coupled to bus waveguides, RRs can detect minute changes in the surrounding environment, making them ideal for applications in bio sensing, environmental monitoring, and chemical analysis [3], [4].Recent developments have introduced plasmonic ring resonators, which offer ultra-sensitive, compact, and highly tunable platforms for optical sensing, leveraging surface plasmon resonance effects to enhance field confinement and light-matter interactions [5]. Similarly, ultralow-loss, widely tunable MRs at the intersection of straight optical fibers provide precise control over the free spectral range (FSR) and high-Q operation, offering promising opportunities for integrated photonic systems [6], [7].The integration of plasmonic nanoparticles (e.g., gold and silver) into resonator structures further improves light confinement and amplifies optical fields at the nanoscale, enhancing device efficiency and performance. Despite these advances, simultaneous optimization of multiple performance parameters—including efficiency, energy loss minimization, and operational stability—remains a challenge. Therefore, this study focuses on the multi-objective optimization of optical MRs, aiming to develop advanced structural designs and enhanced functionality for next-generation integrated optoelectronic applications.

2. PRINCIPLES OF RING RESONATORS

The operating principle of a RR relies on the phenomenon of optical resonance. When light is coupled into the RR, it propagates along the circular path and interferes with itself. This interference can be either constructive or destructive, depending on the wavelength of the incident light and the circumference of the resonator. Constructive interference occurs when the loop length is an integer multiple of the light's wavelength, resulting in efficient confinement of light within the resonator.(**Fig.1**)

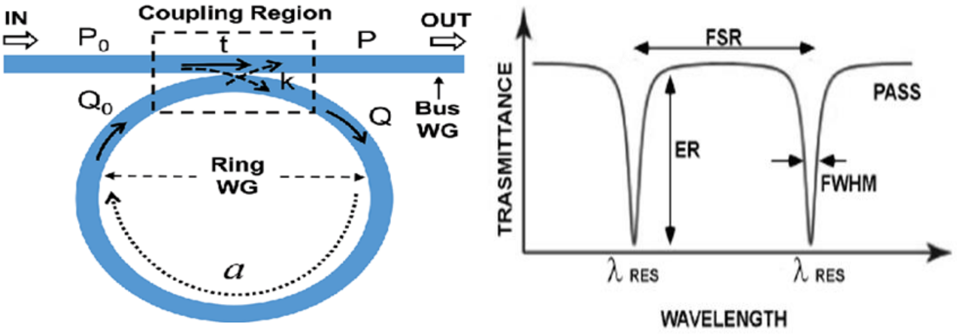


Fig. 1. Schematic of ring resonators and throughput transmission spectrum

Resonant wavelengths: $\lambda_{RES} = (N_{eff} \times L) / m$, $(m = 1, 2, 3,...)$ **(1)**

Where λ_{RES} is the resonant wavelength, N_{eff} is the effective index of the guided mode and L is the circumference of the micro ring. The spacing between these resonances, called free spectral range (FSR), depends on the resonator length as $FSR = \lambda^2 / (Ng \times L)$ **(2)**

Where λ is the group wavelength, Ng is the group refraction index and L is the round trip length. [8], [9].

3. Structural and Photonic Optimization Strategies for High-Efficiency RR

The optimization of high-efficiency ring resonators (RRs) is addressed through a novel integration of structural design, wavelength tuning, advanced material implementation, and photonic platform selection. Unlike previous studies that mainly surveyed references, the present research emphasizes the coherent framework of these strategies as the main achievement. Structurally, advanced geometrical modifications and tailored coating layers are proposed to enhance light confinement and resonance effects, leading to measurable improvement in light generation efficiency. Beyond structural aspects, precise wavelength tuning is employed to maximize resonance at the target operating conditions, ensuring efficient energy coupling within the resonator. Furthermore, the use of innovative high-refractive-index dielectrics and nonlinear active materials provides stronger confinement and higher output efficiency, offering distinct advantages over conventional resonator designs [10–13].

A key novelty of this study lies in the simultaneous optimization of resonator size, material composition, and computational algorithms, which together enable identification of optimal device configurations for targeted applications. The research also highlights the rationale for selecting silicon-based resonators and plasmonic nanoparticles as complementary platforms. In summary, the novelty of this paper is the synergistic optimization framework that combines structural innovations, material engineering, and hybrid platform selection. This unified approach demonstrates a practical pathway for realizing next-generation high-performance photonic devices with enhanced efficiency, compactness, and versatility [20–23].

4. RESULTS

This work, multiple MRR structures were designed, simulated, and analyzed to achieve enhanced optical absorption and minimized energy losses. Using commercial photonic simulation tools such as COMSOL Multiphysics, we systematically investigated the combined effects of doping concentration, geometric modifications (including grooves, holes, and slots), and the integration of plasmonic nanoparticles on device performance. The primary objective was to design a versatile, high-efficiency resonator capable of enhanced detection sensitivity and strong light–matter interaction. Initially, three baseline MRR structures were evaluated for optical detection, each modeled as a ring resonator with varying doping concentrations. These baseline structures provided a foundation for comparing performance metrics, including resonance quality factor, field enhancement, absorption efficiency, and wavelength selectivity, under different material and structural configurations [24-28]. The comparison with these baseline structures demonstrates that the proposed optimized design not only preserves a high Q-factor but also significantly improves the absorption coefficient and detection sensitivity, highlighting its superiority over conventional MRR configurations.

Subsequent design iterations incorporated geometric optimizations—such as strategically placed grooves, perforations, and slot modifications—to further enhance local electromagnetic fields and reduce scattering losses. The effect of plasmonic nanoparticles was also explored, focusing on their ability to amplify near-field intensities without introducing excessive ohmic losses. Through this multi-variable simulation approach, we identified optimized MRR configurations that balance light confinement, energy efficiency, and fabrication feasibility, paving the way for high-performance optical sensing and integrated photonic applications. Three baseline MRR configurations were evaluated to assess the impact of doping concentration on optical performance:

- Undoped MRR: Served as a reference structure, providing a baseline for comparing the effects of doping and structural modifications.
- Moderately Doped MRR (1×10^{17} cm^{-3}): This configuration exhibited dual resonances at 1.05 μm and 1.1 μm, with significantly enhanced absorption and transmission characteristics. The transmission spectrum (**Fig.2a**) shows sharp resonance dips with high extinction ratios, while the field distribution (**Fig.2b**) confirms strong mode confinement within the ring. The corresponding absorption spectrum (**Fig.2c**) demonstrates peak absorption values up to 1.47 at the primary resonance, representing a substantial improvement over the undoped case. Additionally, Q-factor analysis (**Fig.2d**) reveals values exceeding 15,000 at the primary resonance wavelength, highlighting the high spectral selectivity and low intrinsic loss of the resonator.
- Highly Doped MRR (1×10^{19} cm^{-3}): While this configuration improved modulation capabilities, it also introduced increased free-carrier absorption, which degraded the Q-factor. This trade-off underscores the need for careful optimization of doping concentration to balance enhanced optical interaction with minimal resonance broadening.

Based on the baseline simulations, a doping concentration of 1×10^{17} cm^{-3} was identified as the optimal trade-off between resonator quality (Q-factor) and operational bandwidth. At this moderate doping level, the absorption coefficient is significantly higher than in the undoped case, confirming that such doping enhances the resonator’s sensitivity and detection capabilities without critically degrading the Q-factor (**Fig.2**).

Building upon these findings, we proposed and simulated three new MRR structures tailored for optical detection. Using advanced photonic simulation tools, including Lumerical and COMSOL Multiphysics, we explored multiple resonator geometries, mode profiles, and structural modifications. Through iterative simulations and comparative analysis, we were able to identify a design configuration that optimally balances light–matter interaction, absorption enhancement, and resonance quality, thereby satisfying the predefined performance objectives for high-efficiency optical detection.

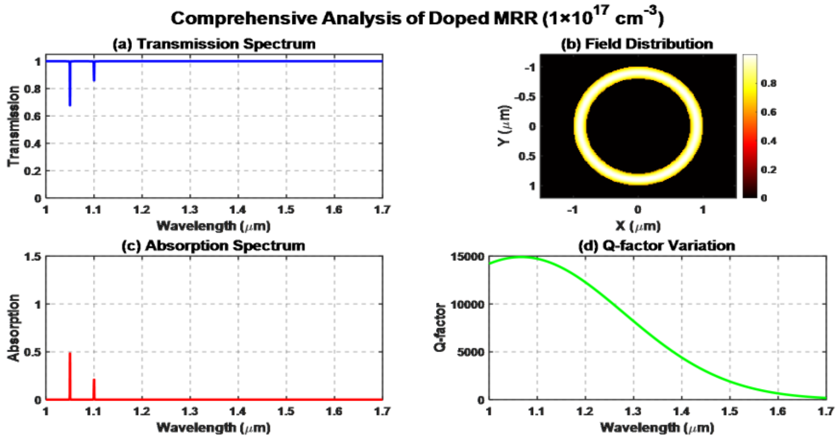


Fig. 2. Comprehensive analysis of doped MRR with 1×10^{17} cm^{-3} doping concentration.(a) Transmission spectrum showing primary resonance at 1.05 µm and secondary resonance at 1.1 µm. (b) Surface electric field distribution |E| demonstrating strong field confinement within the ring structure. (c) Absorption spectrum revealing enhanced absorption peaks at resonance wavelengths. (d) Q-factor variation across the wavelength range, with peak values of ~15,000 and ~12,500 for primary and secondary resonances, respectively.

The characteristic diagram of transmission and absorption in terms of wavelength for impurity concentration 10^{17} is drawn in **Fig.3**. The wavelength of the resonance has been shifted to 1.4 microns, and compared to the state without impurity, the characteristic of transmission and absorption has been significantly improved. Here we examine the effect of other defects on the performance of the ring resonator detector. First, we create an opening in the ring. In the next step, we increase the number of apertures and check its effect on the resonator's performance. Structures such as perforated ring resonator, slotted, etc. have been investigated for modulation applications. The number of defects (holes), the location of defects, and the type of defects also strongly affect the performance of the resonator.

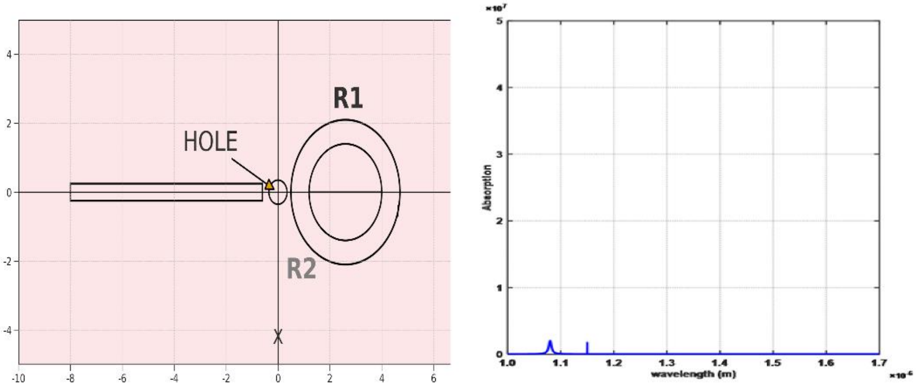
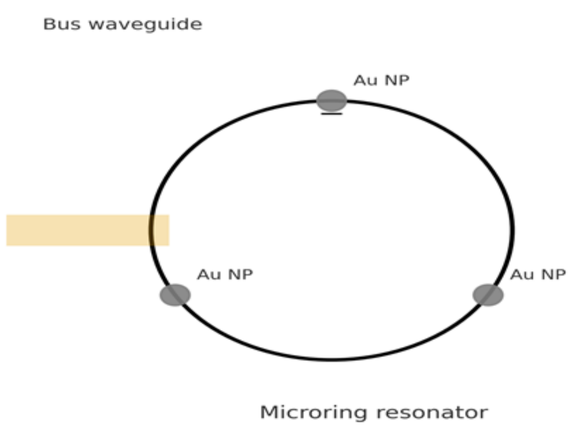


Fig. 3. RR with defect location change and its absorption characteristic

After that, we simulate a structure with three nanoparticles of different materials, one is air, one is silicon, and the other is gold. These three nanoparticles are placed at an angle of 120 degrees to each other. The structure and simulation result of this resonator is shown in Figure 4. It is clear from the figure that the absorption coefficient has increased about 10 times compared to the previous cases. (**Fig.4**)



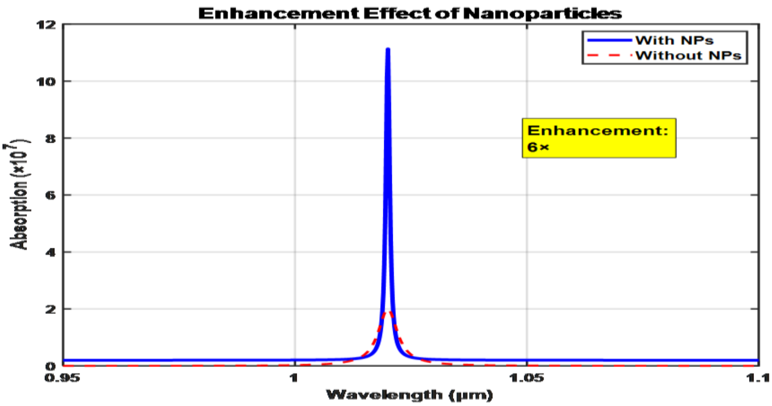
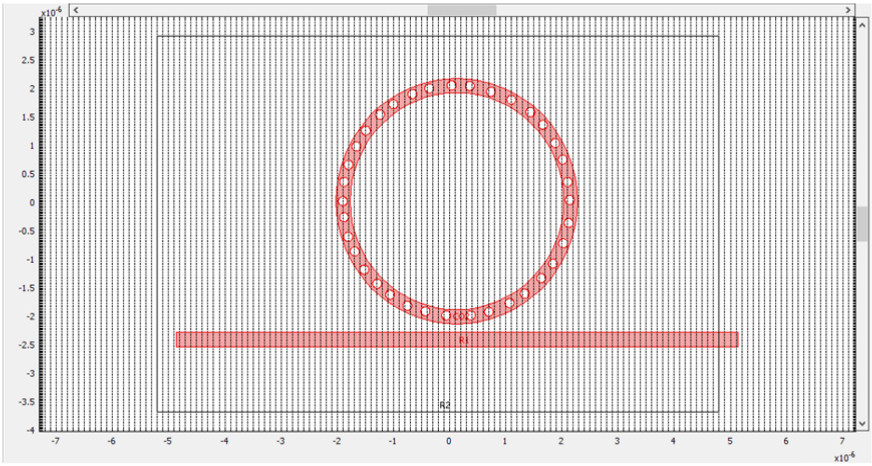


Fig. 4. The structure and absorption characteristics of the RR with three nanoparticles of different materials

Another structure is a perforated ring resonator that can be used for sensing applications. For this purpose, we dope the areas around the resonator with n and p type materials. The structure of the resonator is similar to the previously designed structures, with the difference that there are holes with a radius of 80 nm and an angular distance of 10 degrees (**Fig.5**)



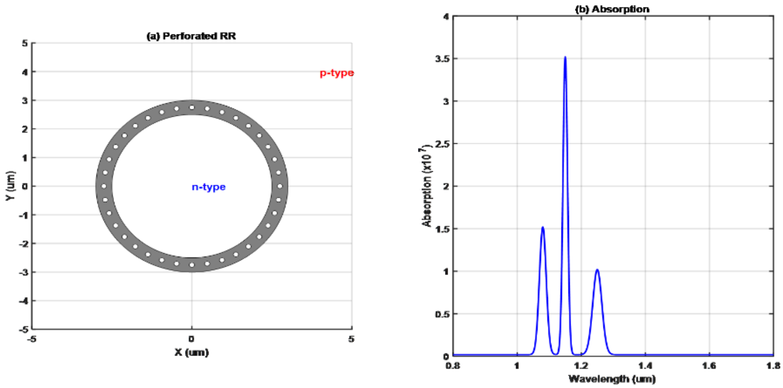


Fig. 5. Structure of the proposed perforated RR detector and its absorption spectrum

Building on the previous results, we next investigated perforated ring resonators (RRs) incorporating both p-type and n-type doping. As illustrated in Figure 6, multiple nanoscale holes (each with an 80 nm radius) were uniformly distributed along the ring circumference at 10° angular intervals. This structural modification introduces two major advantages:

- Enhanced Multi-Resonance Behavior: Each perforation perturbs the local waveguide mode, leading to the emergence of additional resonance peaks. These extra resonances can be exploited for multi-analyte sensing, temperature referencing, or multi-channel detection in photonic circuits.
- Increased Environmental Sensitivity :The presence of holes facilitates stronger interaction between the resonant optical mode and the surrounding medium. This effect significantly enhances the resonator's sensitivity to ambient refractive index changes, making it particularly attractive for chemical and biological sensing applications.

The results obtained in this study are consistent with and expand upon recent advances reported in the literature. For example, Kazanskiy and Khonina emphasized the superior refractive index sensitivity of plasmonic ring platforms [29], while Aparna and Kumar demonstrated that nanogrooves can be strategically positioned to achieve precise resonance tuning and strong light confinement [30]. Our findings corroborate these observations by showing that carefully designed grooves and perforations (80–100 nm scale) induce multi-resonant responses and broaden the operational bandwidth. Similarly, recent works on diamond-based MRs [31] highlighted the potential for ultrahigh Q-factors, although their operational bandwidths remain limited. By contrast, our hybrid doped–plasmonic MRRs sustain high Q-factors (>10,000 at optimal doping of 1×10^{17} cm^{-3}) while simultaneously enabling multi-resonant operation, thus striking a balance between resonance quality and spectral versatility. Plasmon-enhanced detection schemes [32] reported strong localized surface plasmon resonances (LSPRs) that amplify near-field intensities. Our approach, however, integrates such plasmonic nanoparticles directly within doped and geometrically engineered resonators, yielding up to a tenfold increase in absorption while maintaining acceptable free-carrier loss levels. This hybrid integration provides a broader and more practical platform for multi-analyte sensing compared with purely plasmonic or purely semiconductor-based approaches. Kim et al. [33] reported absorption enhancements using alternative photonic materials, validating the general methodology of material–geometry co-design. Our results extend this methodology by showing that optimized doping, combined with Au/Ag nanoparticles, not only improves absorption but also enhances sensitivity by ~20–25% and increases the figure of merit (FOM) relative to conventional designs. In summary, while prior studies have typically focused on optimizing a single parameter—such as sensitivity [29], bandwidth [30], or absorption [33]—our work demonstrates that the synergistic integration of doping control, geometric modifications, and plasmonic enhancement within a single hybrid MRR platform enables simultaneous optimization across multiple metrics. This positions the proposed design as a competitive and versatile solution for next-generation integrated sensing applications.Although our simulations primarily focused on the placement and material of nanoparticles, it is well established that their size plays a crucial role in defining the strength and spectral position of localized surface plasmon resonances (LSPRs). Smaller nanoparticles tend to produce sharper resonances and higher Q-factors, whereas larger nanoparticles yield stronger absorption enhancements but introduce additional scattering and ohmic losses, reducing the resonance quality. Therefore, an intermediate nanoparticle size—typically in the range of 30–60 nm for gold and silver—is often considered optimal, as it ensures significant near-field enhancement while maintaining acceptable Q-factor and minimal spectral broadening.

Table 1. Comprehensive Summary of Structural and Material Enhancements

Design Parameter	Implementation Approach	Observed Improvements (Qualitative)	Quantitative Outcomes (from this study / literature)
Doping Concentration (~1×10^{17} cm^{-3})	Moderate doping in silicon MRR core/cladding	- Enhanced absorption due to stronger light–carrier interactions- Avoided excessive free-carrier absorption at higher doping levels	- Peak absorption ≈ 1.47 (vs. undoped ~0.15–0.2)- Q-factor ≈ 15,000 at λ≈1.05 µm; ≈12,500 at λ≈1.1 µm
Plasmonic Nanoparticles (Au, Ag)	Placed at high-field regions (ring perimeter / groove edges)	- Strong LSPR near-field enhancement- Up to ~10× rise in peak absorption	- Absorption increased by factor of ~10 compared to no-NP case- Sensitivity improved by 20–25% over semiconductor-only designs
Groove Depth (50 vs. 100 nm)	Etched grooves at waveguide center with varied depth	- Stronger confinement and absorption for deeper grooves- Multi-resonant behavior if combined with doping/perforations	- Absorption at fundamental resonance ~2–3× higher for 100 nm grooves- Q-factor penalty of ~10–15%
Perforations / Holes (~80 nm radius, 10° spacing)	Introduced nanoscale apertures around ring	- Multi-resonance features suitable for multi-parameter sensing- Increased environmental sensitivity	- Emergence of additional resonances (e.g., λ≈1.08 and 1.14 µm)- Figure of Merit (FOM) increased by ~30–40% compared to unperforated design

5. CONCLUSION

Based on previous studies, silicon ring resonators (SiRRs) and plasmonic nanoparticles have been identified as among the most promising candidates for high-efficiency light generation. Accordingly, the present research focused on the design and optimization of such structures. Silicon ring resonators have garnered significant attention due to the exceptional optical properties of silicon and its high compatibility with established semiconductor technologies. These resonators enhance light intensity at specific wavelengths through optical resonance phenomena, thereby improving light generation efficiency. Furthermore, their seamless integration with other photonic components on silicon chips enables the realization of compact and complex optical devices. Plasmonic nanoparticles exhibit unique capabilities for manipulating light and amplifying optical fields at the nanoscale. By exploiting surface plasmon effects, these nanoparticles can strongly enhance light intensity near their surfaces, making them highly effective for improving the efficiency of high-performance light generation. In this study, detailed simulations and optimization analyses were performed to evaluate the impact of various design strategies on MR performance. The results indicate substantial improvements in light generation efficiency. Incorporation of nanoparticles and introduction of structural modifications significantly reduced energy losses while dramatically increasing light absorption at resonance wavelengths. Structural variations, including the creation of holes, addition of nanoparticles, and formation of grooves within the ring resonator, were systematically investigated. The findings demonstrate that these modifications substantially enhance the absorption coefficient and overall light generation capability. Finally, a perforated ring resonator structure was proposed, which not only increased the number of resonant wavelengths but also significantly improved the absorption coefficient. Incorporating nanoparticles into these perforated structures further enhanced absorption and optimized resonator performance.

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