HIGH-QUALITY FACTOR BIOSENSOR USING 2D RING RESONATOR OPTICAL FILTER

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Introduction:

Pressure sensing is an essential requirement across numerous fields, including biomedical monitoring, industrial automation, environmental analysis, and aerospace engineering. Traditional pressure sensors, such as resistive, capacitive, and piezoelectric sensors, face significant limitations including susceptibility to electromagnetic interference, reduced sensitivity at micro-scales, difficulty in achieving high Quality factor (Q-factor), and challenges in miniaturization. As technological demands continue to grow, there is an urgent need for sensing devices that offer high precision, compactness, stability, and immunity to noise.

Optical sensing technologies have emerged as a powerful alternative to overcome these limitations. Among them, photonic crystal-based sensors have gained extensive attention due to their ability to manipulate and confine light using periodic dielectric structures. Photonic crystals generate photonic bandgaps — frequency ranges in which light propagation is restricted — allowing highly controlled optical confinement. When a defect is introduced in the photonic crystal lattice, it creates a localized cavity that supports strong resonance modes sensitive to external parameters such as pressure, refractive index, or temperature.

Two-dimensional (2D) photonic crystals offer advantages in fabrication, integration, and light confinement. Their planar structure makes them suitable for on-chip integration in compact photonic circuits. Integrating a 2D ring resonator inside the photonic crystal further enhances sensor performance by allowing circulating light to interact multiple times with the sensing region, resulting in sharper resonance peaks, stronger optical confinement, and a significantly higher Q-factor. The project titled "High-Quality Factor Biosensor Using 2D Ring Resonator Optical Filter" focuses on designing and simulating such an advanced optical pressure sensor using Finite Element Method (FEM) tools.

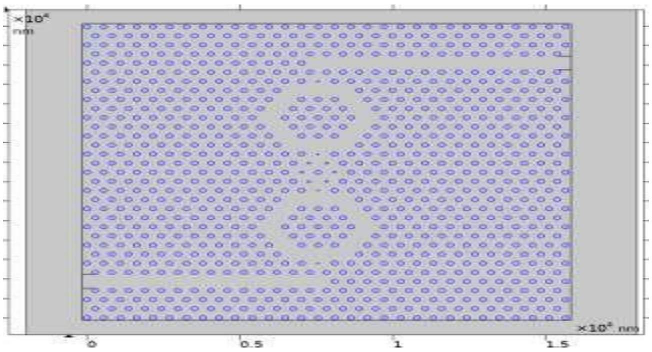


Figure 1: Biosensor Using 2d Ring Resonator Optical Filter

Objectives:

1. To design a two-dimensional photonic crystal-based pressure sensor with an integrated ring resonator structure for enhanced optical confinement.
2. To enhance optical confinement and achieve sharper resonance peaks for improved sensing performance and higher Quality factor (Q-factor).
3. To simulate electromagnetic wave propagation using the Finite Element Method (FEM) in COMSOL Multiphysics for precise performance analysis and resonance identification.
4. To evaluate the effects of pressure and temperature variations through parametric sweeps to ensure robust and thermally stable operation in real-world environments.
5. To explore multi-channel sensing capabilities for improved functionality and simultaneous detection across multiple resonance wavelengths.
6. To validate the proposed sensor design for applications in biomedical diagnostics, industrial monitoring, and aerospace systems.

Methodology:

The methodology begins with designing the 2D photonic crystal lattice composed of periodic dielectric rods or holes arranged in a suitable geometry, with a ring resonator embedded within the lattice to enhance optical confinement. Key structural parameters such as lattice constant, radius of rods, refractive index, defect cavity size, and ring resonator width are defined. Photonic bandgap properties are analyzed to ensure that the structure supports strong resonance modes suitable for sensing applications.

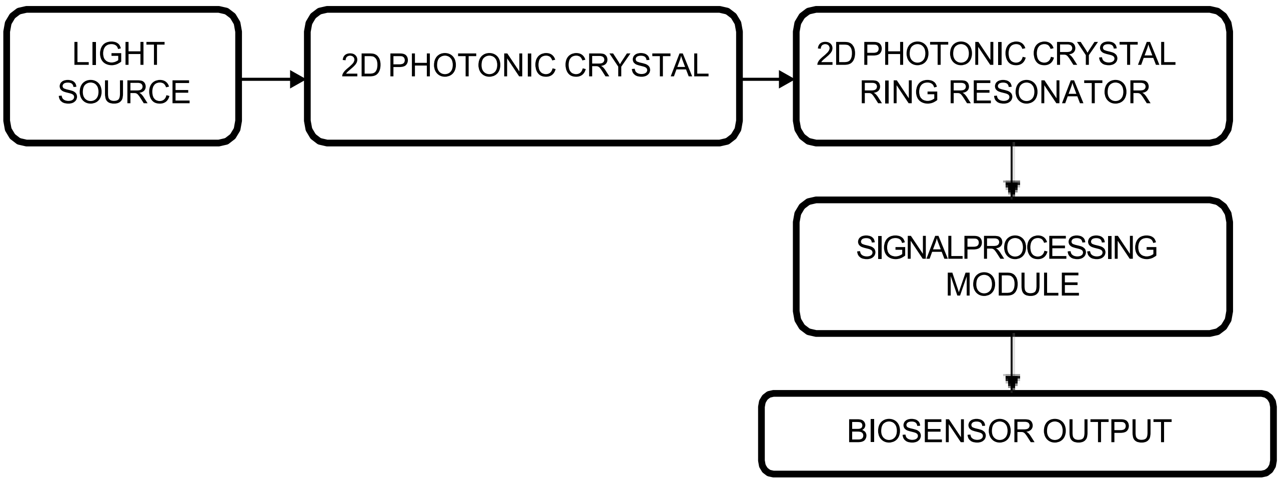


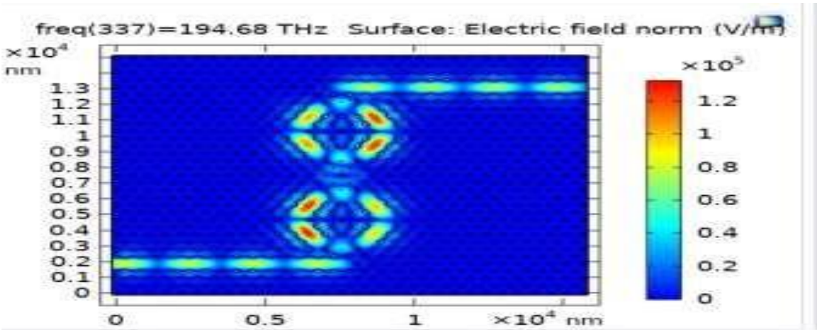
Figure 2: Block diagram illustrates the signal flow in a hybrid photonic crystal pressure sensor

A Finite Element Method (FEM)-based simulation platform — COMSOL Multiphysics with the Wave Optics Module — is used to model electromagnetic wave propagation and resonance effects. The model is meshed with fine triangular elements and boundary conditions (Perfectly Matched Layers) are applied to absorb outgoing waves. A broadband optical source is introduced and the transmission spectrum is extracted to identify resonance modes with high Q-factor peaks.

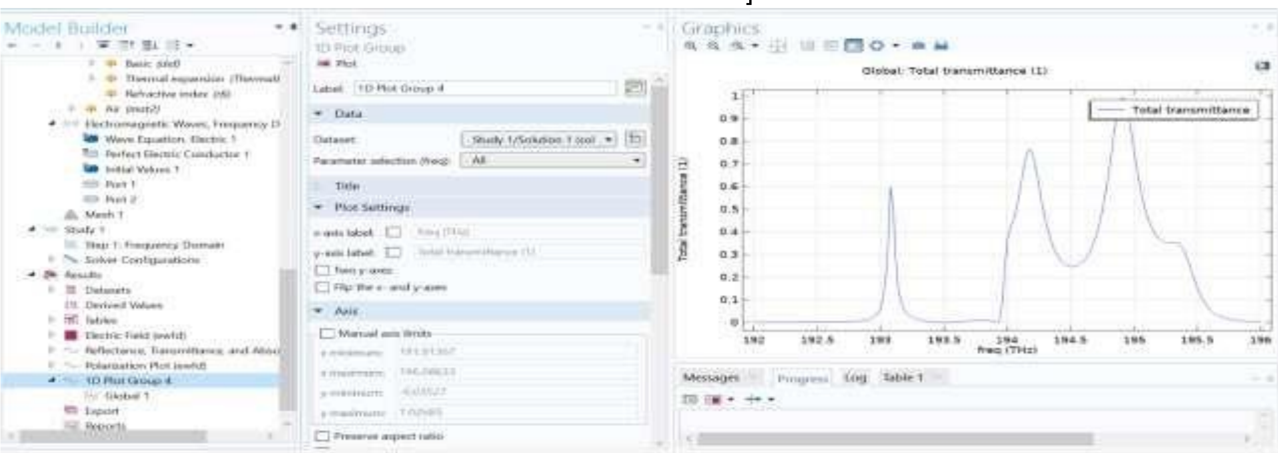
Parametric sweeps simulate pressure variations, incorporating mechanical deformation and refractive index changes. The corresponding resonance shifts are recorded to calculate sensor sensitivity (wavelength shift per unit pressure). Temperature-dependent sweeps further ensure thermal stability. The design is also optimized for multi-channel operation by identifying multiple resonance peaks within the photonic bandgap that respond to pressure independently.

Result and Conclusion:

In conclusion, the design and simulation of the High-Quality Factor Biosensor using a 2D Photonic Crystal Ring Resonator successfully demonstrate the potential of photonic structures in achieving highly accurate and reliable pressure sensing. By integrating a two-dimensional photonic crystal lattice with a ring resonator cavity, the system provides exceptional light confinement and sharp resonance peaks, resulting in a significantly enhanced Quality factor (Q-factor). This strong optical confinement allows the sensor to detect even minute changes in pressure through measurable shifts in resonance wavelength caused by refractive index variations or geometric deformation.



[Figure 3: Electric field norm distribution showing dual photonic crystal ring resonators with coupled waveguides at 194.68 THz.]



[Figure 4: Total transmittance spectrum of the photonic crystal resonator showing resonance peaks in the 192–196 THz range.]

FEM-based simulations confirm that the sensor exhibits excellent sensitivity, stability, and precision. The ability to perform parametric sweeps and evaluate multi-channel operation further strengthens the robustness and versatility of the design. The compact structure and optical nature of the sensor provide key advantages including immunity to electromagnetic interference, low power consumption, scalability, and suitability for integration into modern photonic circuits. These features make the proposed biosensor an ideal candidate for applications in biomedical diagnostics, industrial instrumentation, environmental monitoring, and aerospace systems

Project Outcome & Industry Relevance:

The project successfully demonstrates the design of a 2D photonic crystal ring resonator biosensor with improved sensing performance. It achieves a high-quality factor with sharp resonance peaks, enabling accurate and reliable detection. The system effectively identifies wavelength shifts caused by changes in refractive index and pressure variations. Simulation results using COMSOL validate the performance and accuracy of the proposed design. The developed sensor is compact, efficient, and immune to electromagnetic interference, making it highly dependable. It provides high sensitivity suitable for real-time monitoring applications. This technology has strong relevance in the biomedical and healthcare industry for biosensing and diagnostic purposes. It can also be applied in aerospace and defense sectors for precise environmental and pressure sensing. The project is significant for telecommunication and photonics industries, especially in integrated optical systems. It supports the advancement of lab-on-chip devices and miniaturized sensor technologies. The design aligns with current industry trends focusing on optical sensing, high precision, and compact systems. Furthermore, it has great potential for integration into IoT-based smart devices and future wearable sensing applications.

Working Model Vs. Simulation/Study:

A simulation or study-based model focuses on designing and analyzing the system using software tools like COMSOL, without physically building the device. It allows precise control over parameters such as geometry, materials, and boundary conditions, making it easier to optimize performance like Q-factor and resonance. Simulation is cost-effective, time-saving, and useful for testing multiple design variations quickly. However, it may not capture all real-world factors such as fabrication errors, material imperfections, and environmental noise. In contrast, a working model involves physically fabricating the sensor and testing it in real conditions. It provides practical validation of the design and confirms whether the simulated results can be achieved experimentally. A working model helps identify real-time challenges like losses, instability, and measurement errors. However, it requires more resources, fabrication facilities, and time. While simulations are ideal for initial design and optimization, working models are essential for real-world implementation and industry readiness. Both approaches together ensure a complete and reliable development process.

Project Outcomes & Learnings:

1. Successfully designed a 2D photonic crystal ring resonator biosensor.
2. Achieved high Q-factor with sharp resonance peaks for accurate sensing.
3. Demonstrated wavelength shift detection due to refractive index changes.

4. Validated the design using COMSOL and FEM-based simulations.
5. Developed a compact and efficient optical sensing system.
6. Gained strong understanding of photonic crystal and optical sensing concepts.
7. Learned practical usage of COMSOL Multiphysics simulation tools.
8. Improved knowledge of Finite Element Method and electromagnetic analysis.
9. Developed skills in design optimization and parameter tuning.

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Future Scope:

The future scope of this project includes the fabrication of the designed 2D photonic crystal ring resonator for real-time experimental validation. Further improvements can be made by enhancing the Q-factor and sensitivity using advanced materials such as graphene or silicon-on-insulator structures. The design can be extended to support multi-parameter sensing, including pressure, temperature, and gas detection within a single device.
Integration with microfluidic systems can enable efficient biosensing for medical diagnostics. The sensor can be developed into a lab-on-chip device for compact and portable healthcare applications. Incorporating artificial intelligence and machine learning algorithms can improve data analysis and enable smart sensing capabilities. The system can be optimized for low power consumption, making it suitable for wearable and battery- operated devices. Future work can also focus on improving fabrication techniques to reduce losses and increase reliability. The design can be scaled for mass production using

semiconductor fabrication technologies. Integration with optical communication systems can enhance its applications in photonic circuits. The sensor can be adapted for environmental monitoring, including pollution and toxic gas detection. Further research can explore tunable photonic crystal structures for dynamic sensing applications. The project can be extended to 3D photonic crystal designs for improved performance. It also has potential applications in defense and aerospace for high-precision sensing. Integration with IoT platforms can enable remote monitoring and real-time data transmission. Overall, the project has strong potential for commercialization and deployment in next-generation smart sensing systems.