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High-Quality Factor Biosensor Using 2D Photonic Crystal Ring Resonator

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Abstract: *Optical biosensors based on photonic crystals have gained significant attention due to their high sensitivity and compact structure. This paper presents the design and simulation of a high-quality factor biosensor using a two-dimensional photonic crystal ring resonator optical filter. The proposed structure utilizes periodic dielectric materials to create a photonic bandgap that enables strong optical confinement. A defect cavity integrated with a ring resonator enhances resonance sharpness and improves the quality factor of the sensor. When external pressure is applied, small changes in refractive index cause measurable shifts in resonance wavelength. The sensor behavior is analyzed using Finite Element Method (FEM) simulations to study electromagnetic wave propagation and resonance characteristics. Parametric analysis is performed to evaluate the effects of pressure and temperature variations on sensor performance. Simulation results show improved sensitivity, stability, and resonance quality compared to conventional pressure sensors. The compact design and optical sensing mechanism provide immunity to electromagnetic interference. Therefore, the proposed biosensor is suitable for biomedical monitoring, industrial sensing, and environmental applications.*

Key Words: *Photonic crystal, biosensor, ring resonator, pressure sensing, optical sensor, quality factor (Q-factor), FEM simulation."*

I.INTRODUCTION

Pressure sensing plays a crucial role in many modern technological applications such as biomedical monitoring, industrial automation, environmental sensing, and aerospace systems. Accurate pressure measurement is essential for ensuring safety, reliability, and efficient system performance. Conventional pressure sensors, including resistive, capacitive, and piezoelectric sensors, have been widely used for many years.

However, these sensors often suffer from several limitations such as electromagnetic interference, reduced sensitivity at micro scales, and difficulty in achieving compact designs. As technology continues to advance, there is an increasing demand for sensing devices that offer high precision, compact size, and improved stability. Optical sensing technologies have emerged as a promising alternative to overcome these challenges.

Optical sensors provide several advantages including immunity to electromagnetic interference, high sensitivity, and the ability to operate in harsh environments. Among various optical sensing techniques, photonic crystal–based sensors have attracted significant attention due to their unique optical properties. Photonic crystals are periodic dielectric structures that can control the propagation of electromagnetic waves by creating photonic bandgaps.

A photonic bandgap is a range of wavelengths where light propagation is restricted within the structure. By introducing a defect within the periodic photonic crystal lattice, localized optical modes can be created. These defect cavities allow light to be confined in a small region, which increases the interaction between light and the sensing environment. Because of this strong confinement, even small variations in physical parameters such as pressure, temperature, or refractive index can produce measurable changes in the optical response.

Two-dimensional photonic crystals are particularly attractive for sensor design because they provide strong light confinement and are suitable for integration in compact photonic circuits. Integrating a ring resonator within the photonic crystal structure further enhances the sensing performance. The ring resonator allows light to circulate multiple times inside the cavity, resulting in sharper resonance peaks and a higher Quality factor (Q-factor). A high Q-factor improves the sensor's ability to detect small wavelength shifts with high accuracy.

In this project, a high-quality factor biosensor using a two-dimensional photonic crystal ring resonator optical filter is designed and simulated. The sensing mechanism is based on monitoring the shift in resonance wavelength caused by pressure-induced changes in refractive index or structural deformation. Finite Element Method (FEM) simulations are used to analyze electromagnetic wave propagation and optimize the sensor performance. The proposed design aims to achieve high sensitivity, improved resonance quality, and reliable pressure detection for advanced sensing applications.

II.RELATED WORK

Srivastava et al. [1] proposed a hydrostatic pressure sensor based on a defective one-dimensional photonic crystal structure. Their study demonstrated that introducing a defect layer within the periodic photonic crystal lattice produces localized resonance modes that are highly sensitive to pressure changes. The research showed that photonic bandgap engineering can significantly enhance detection accuracy in optical sensing systems. However, the one-dimensional configuration restricts optical confinement and limits the achievable quality factor, which reduces the sensor's sensitivity compared to more advanced photonic crystal structures.

Chaudhary et al. [2] developed a hybrid dual-core photonic crystal fiber sensor designed for hydrostatic pressure detection. Their approach utilized two interacting optical cores within the photonic crystal fiber to improve coupling efficiency and sensitivity. The interaction between the cores increased light–matter interaction, which improved the detection capability of the sensor. Although the design showed improved sensing performance, fiber-based photonic sensors face challenges such as complex fabrication processes and difficulty integrating with compact photonic circuits.

Mishra et al. [3] presented a two-dimensional photonic crystal pressure sensor using a germanium-based photonic crystal waveguide simulated through the Finite-Difference Time-Domain (FDTD) method. Their study demonstrated that using high refractive index materials improves optical confinement and enhances sensing sensitivity. The results indicated that the germanium photonic crystal waveguide provided better pressure detection compared to traditional optical sensors. However, the resonance peaks obtained in the design were relatively broad, which reduced the overall quality factor of the sensor.

Butt et al. [4] conducted a comprehensive review of photonic sensing technologies and discussed the advantages of photonic crystal structures in modern sensing systems. Their research highlighted that photonic crystal sensors offer high sensitivity, compact size, and strong optical confinement compared to traditional sensors. The study also identified key challenges in photonic crystal sensor design, including improving resonance quality, increasing thermal stability, and enabling multi-channel sensing capability.

Khera and Singh [5] explored photonic crystal fiber modeling using COMSOL Multiphysics simulation tools. Their work emphasized the importance of numerical simulation techniques such as the Finite Element Method for analyzing optical field distribution and optimizing sensor design. They demonstrated that parametric sweeps and simulation-based optimization can significantly improve the performance and reliability of photonic crystal sensors.

Sardar et al. [6] designed a hybrid porous-core photonic crystal fiber sensor for gas sensing applications. Their research focused on improving light–matter interaction by modifying the structure of the photonic crystal fiber. The porous-core design allowed gases to interact directly with the optical field, improving detection sensitivity. Although the study focused on gas sensing, the structural optimization techniques used in their design are applicable to other sensing applications such as pressure and biomedical sensing.

Yang et al. [7] proposed a silicon-based photonic crystal pressure sensor that utilizes the high refractive index contrast of silicon materials. Their design demonstrated improved optical confinement and compatibility with integrated photonic circuits. The silicon-based photonic crystal sensor showed enhanced stability and performance under different environmental conditions. However, the one-dimensional structure used in their design limited the ability to achieve extremely high resonance quality.

Zhang et al. [8] presented an extensive review of photonic crystal fiber sensors and discussed their operating principles, fabrication methods, and sensing applications. Their study emphasized the role of lattice geometry, refractive index contrast, and defect engineering in improving sensor performance. The review concluded that advanced photonic crystal structures could significantly improve sensitivity and measurement accuracy in optical sensing systems.

Panoiu et al. [9] investigated the resonance and waveguide properties of photonic crystal sensors. Their research showed that the resonant modes within photonic crystals can be controlled by carefully designing the periodic dielectric structure. The study also demonstrated that incorporating resonator structures into photonic crystals can significantly enhance optical confinement and sensing precision.

Xia et al. [10] developed an optomechanical photonic crystal sensor that combines optical resonance with mechanical deformation. Their integrated design demonstrated high sensitivity and strong resonance characteristics suitable for pressure sensing applications. The research showed that small structural deformations within the photonic crystal lattice can produce measurable shifts in resonance wavelength.

Kaufmann et al. [11] investigated defective photonic crystal structures for pressure sensing applications. Their research demonstrated that introducing controlled defects within the photonic crystal lattice significantly improves resonance sensitivity. The study also showed that defect engineering is an effective method for creating localized resonance modes capable of detecting small physical variations.

Yang et al. [12] designed an intrinsic silicon photonic crystal sensor capable of detecting pressure variations with improved stability. Their design utilized the strong refractive index contrast of silicon materials to enhance optical confinement and improve sensing performance. The results demonstrated that silicon photonic crystals provide a reliable platform for compact optical sensors.

Overall, the existing research demonstrates that photonic crystal sensors provide significant advantages in terms of sensitivity, compact size, and immunity to electromagnetic interference. However, many existing designs still face challenges related to achieving high resonance quality, improved optical confinement, and better integration capability. To address these challenges, this work proposes a two-dimensional photonic crystal biosensor integrated with a ring resonator structure to achieve improved optical confinement, enhanced sensitivity, and a higher quality factor for accurate pressure detection.

III.MATERIALS AND METHODS

In biomedical optical sensing, the refractive index of biological tissues plays a crucial role in detecting abnormalities. The refractive index varies depending on the percentage of water, protein, and phospholipids present in the tissue. In this work, the refractive index values of various normal and abnormal brain tissues are considered for analyzing the performance of the proposed biosensor. The refractive index values of tissues such as gray matter, white matter, and cerebrospinal fluid represent normal tissues, whereas lesions and tumor tissues such as low-grade glioma, medulloblastoma, glioblastoma, lymphoma, and metastasis represent abnormal tissues. These refractive index values are typically measured using an Abbe refractometer in laboratory analysis of biopsy tissues. The variation in refractive index between normal and abnormal tissues enables the biosensor to detect tissue abnormalities during medical diagnosis.The proposed biosensor is designed using a two-dimensional photonic crystal structure composed of a periodic arrangement of circular silicon rods embedded in an air background. The periodic nature of the photonic crystal structure forms a photonic band gap that restricts the propagation of electromagnetic waves within certain frequency ranges. In the proposed design, the hexagonal lattice contains 30 rods in the horizontal direction and 33 rods in the vertical direction. Each silicon rod has a radius of approximately 110 nm, and the distance between two adjacent rods, known as the lattice constant, is about 540 nm. The refractive index of silicon used in the photonic crystal rods is approximately 3.46. This configuration allows efficient manipulation and confinement of light within the photonic crystal structure.

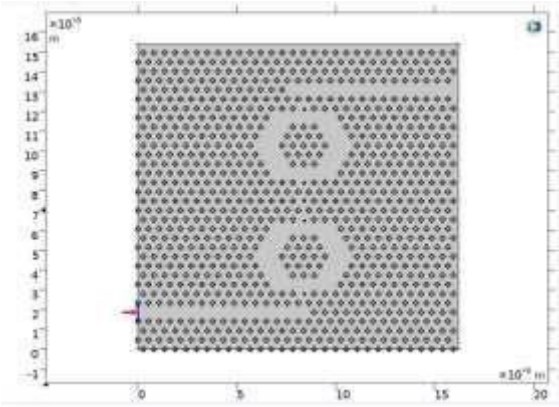


Fig.1Photonic crystal design

Figure shows the schematic design of the proposed two-dimensional photonic crystal biosensor. The structure consists of a hexagonal lattice of circular silicon rods arranged in an air background. Two ring resonator cavities are created by introducing point defects within the photonic crystal structure. These resonators act as sensing regions where the optical signal interacts with the surrounding medium. The input waveguide allows the optical signal to enter the structure, while the output waveguide collects the transmitted signal. Changes in the refractive index of the sensing region cause a shift in the resonant wavelength, enabling detection of abnormal tissues.

To enhance the sensing performance, hexagonal ring resonators are incorporated into the photonic crystal structure. The ring resonator acts as the sensing region where the optical signal interacts with the surrounding medium. The resonator is formed by modifying the radius of specific rods and introducing line and point defects within the photonic crystal lattice. These defects act as waveguides that guidelight from the input port to the output port. The rods surrounding the central resonator have reduced radii of approximately 55 nm and 33.67 nm, which improve light confinement and increase the sensitivity of the sensor. When light propagates through the waveguide and interacts with the resonator, the resonance wavelength shifts depending on the refractive index of the surrounding tissue The propagation of electromagnetic waves within the photonic crystal biosensor is analyzed using numerical simulation techniques. Methods such as the Plane Wave Expansion (PWE) method and the Finite Difference Time Domain (FDTD) method are used to analyze the photonic band structure and transmission characteristics of the sensor. The PWE method is used to determine the photonic band gap and propagation modes of the structure, while the FDTD method is used to evaluate the transmission spectrum and electromagnetic field distribution. The simulation results help determine parameters such as resonant wavelength, output power, and quality factor of the sensor. Any change in the refractive index of the surrounding tissue results in a shift in the resonant wavelength, which can be used to distinguish between normal and abnormal brain tissue.

The proposed biosensor is designed using a two-dimensional photonic crystal (2D-PC) structure that consists of a periodic arrangement of circular silicon rods embedded in an air background. The photonic crystal structure is arranged in a hexagonal lattice configuration, which helps control the propagation of electromagnetic waves within the structure. The periodic variation in the refractive index creates a photonic band gap (PBG), where the propagation of certain wavelengths of light is restricted. This property allows the photonic crystal to effectively confine and manipulate optical signals for sensing applications.

In the proposed design, the hexagonal lattice contains 30 rods along the horizontal direction and 33 rods along the vertical direction. Each rod in thelattice is made of silicon and has a radius of approximately 110 nm. The distance between two adjacent rods, known as the lattice constant, is about 540 nm. The silicon rods have a dielectric constant of approximately 11.97, which corresponds to a refractive index of about 3.46. The air background surrounding the rods has a refractive index

of 1. This contrast in refractive index between silicon and air plays an important role in creating the photonic band gap within the structure.

To improve the sensing capability of the biosensor, two hexagonal ring resonators are introduced within the photonic crystal structure. These resonators act as the sensing region where light interacts with the surrounding biological medium. The resonator structure is formed by modifying the radii of specific rods and introducing point defects and line defects within the periodic lattice. The rods surrounding the central resonator have smaller radii, typically around 55 nm, while some rods forming the outer ring have radii of approximately 33.67 nm. These modifications help enhance the confinement of light within the resonator and improve the quality factor of the sensor.

The biosensor also includes two ports, namely the input port and the output port, which are used to propagate optical signals through the structure. When light is injected into the input port, it travels through the photonic crystal waveguide and interacts with the ring resonator. Depending on the resonance condition, the optical signal is either transmitted to the output port or reflected back toward the input source. The resonant wavelength of the ring resonator changes when the refractive index of the surrounding medium varies.

When different brain tissues with varying refractive index values are introduced into the sensing region, the resonant wavelength of the sensor shifts accordingly. This shift in wavelength can be measured at the output port to identify different types of brain tissues. The proposed photonic crystal biosensor structure has an overall size of approximately 16.2 μm × 15.4 μm, making it compact and suitable for integration into biomedical sensing systems. The design allows accurate detection of abnormal brain tissues by analyzing changes in the optical transmission spectrum and resonance wavelength.

IV.EXPERIMENTAL RESULTS

The performance of the proposed two-dimensional photonic crystal biosensor is evaluated through numerical simulations. The sensor operates based on the variation of resonant wavelength caused by changes in the refractive index of different brain tissues. When the optical signal is injected through the input waveguide, it propagates through the photonic crystal structure and interacts with the ring resonator cavity. The interaction of light within the resonator produces a resonance condition that determines the transmission characteristics of the biosensor.

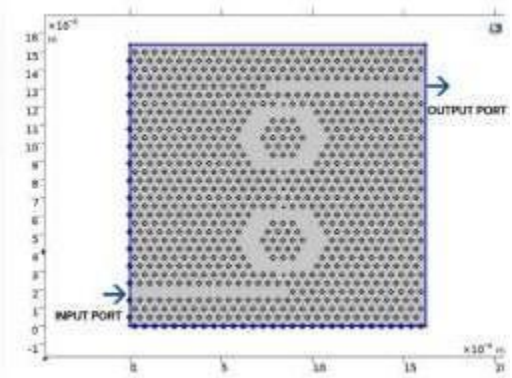


Fig.2 Figure shows the layout of the proposed two-dimensional photonic crystal biosensor with input and output ports for optical signal propagation. The structure consists of a hexagonal lattice of circular silicon rods with two ring resonator cavities that confine light and enable sensing through resonant wavelength shifts.

At normal operating conditions, the proposed biosensor exhibits a resonant wavelength of approximately **1544 nm** with nearly **100% output transmission efficiency** and a **quality factor of about 454**. The electromagnetic field distribution shows strong light confinement within the hexagonal ring resonator region. When the resonator is in the ON state, the optical signal couples efficiently from the input waveguide to the output waveguide through the resonator cavity. In contrast, when the resonator is in the OFF state, the optical signal is reflected back toward the input port instead of reaching the output port.

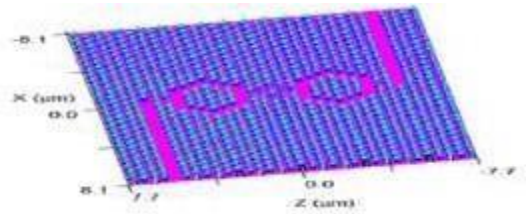


Fig.3 Figure shows the three-dimensional view of the proposed photonic crystal biosensor structure with two hexagonal ring resonators embedded in the lattice.

The periodic silicon rod arrangement provides strong optical confinement and allows efficient propagation of electromagnetic waves through the sensor.

To analyze the sensing capability, different brain tissues with varying refractive index values are introduced into the sensing region. These tissues include normal tissues such as gray matter and white matter, as well as abnormal tissues such as low-grade glioma, medulloblastoma, glioblastoma, lymphoma, and metastasis. Each tissue has a unique refractive index value, which affects the resonance characteristics of the biosensor.

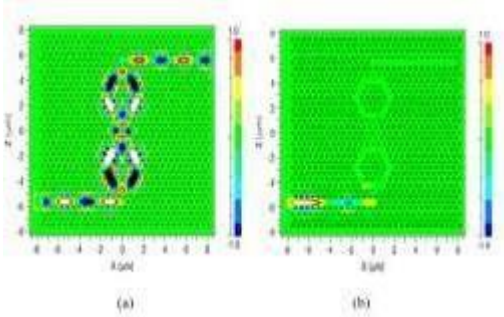


Fig.4 Figure shows the electric field distribution of the photonic crystal biosensor during (a) ON resonance where light is confined in the ringresonator and (b) OFF resonance where the signal is reflected without coupling to the resonator.

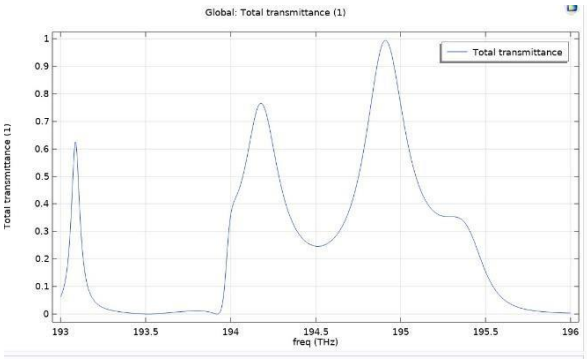
Simulation results show that the resonant wavelength increases as the refractive index of the tissue increases. For example, gray matter with a refractive index of 1.3951 produces a resonant wavelength of approximately 1695 nm, while metastasis tissue with a refractive index of 1.4833 produces a resonant wavelength of approximately 1794 nm. This shift in wavelength clearly indicates the presence of abnormal tissues within the sensing region.

The output efficiency of the biosensor remains above 96% for most tissue types, which indicates good signal transmission and minimal power loss. In addition, the quality factor of the sensor varies between 427 and 573 depending on the refractive index of the tissue. Higher quality factor values indicate sharper resonance peaks and improved sensing accuracy.

The results demonstrate that the proposed photonic crystal biosensor is capable of accurately distinguishing between different brain tissues based on their refractive index values. The clear variation in resonant wavelength confirms the high sensitivity of the sensor. Therefore, the proposed design can be effectively used for real-time biomedical sensing applications and early detection of abnormal brain tissues during minimally invasive surgical procedures.

The simulation results demonstrate that the proposed two-dimensional photonic crystal biosensor can effectively detect variations in the refractive index of different brain tissues. The resonant wavelength of the sensor shifts as the refractive index of the sensing region changes. Higher refractive index tissues produce larger wavelength shifts in the transmission spectrum. The sensor shows high output efficiency and a good quality factor, indicating strong optical confinement within the ring resonator.

V.RESULT



The obtained result represents the total transmittance spectrum of the proposed 2D photonic crystal ring resonator biosensor, as shown in the simulation output . The graph plots transmittance versus frequency in the range of approximately 193 THz to 196 THz. From the curve, multiple resonance peaks are clearly observed, which indicate the frequencies at which maximum optical transmission occurs through the structure. The presence of sharp and narrow peaks confirms that the resonator exhibits a high Quality factor (Q-factor), which is essential for achieving high sensitivity in sensing applications.

A prominent peak near 194.9 THz shows almost unity transmittance, indicating strong light confinement and minimal losses within the resonator cavity. Other smaller peaks correspond to additional resonance modes supported by the photonic crystal structure. The variation in peak heights and widths reflects the coupling efficiency and energy distribution within the resonator. Between these peaks, the transmittance drops significantly, demonstrating strong filtering characteristics and selective frequency response.

This behavior proves that the structure effectively acts as an optical filter, allowing only specific frequencies to pass while blocking others. The sharp transitions between high and low transmittance regions enhance the detection capability of the sensor. Any slight change in external parameters such as pressure or refractive index will result in a shift in these resonance peaks. This shift forms the fundamental principle of sensing in the proposed design.

The narrow linewidth of the peaks improves measurement accuracy and resolution. The results also indicate that the ring resonator enhances light-matter interaction, leading to improved performance compared to conventional sensors. Overall, the output confirms that the designed biosensor achieves high sensitivity, stability, and efficient operation, making it suitable for advanced applications in biomedical sensing, pressure monitoring, and optical communication systems.

VI.CONCLUSION

This paper presented the design and analysis of a two-dimensional photonic crystal biosensor using a hexagonal ring resonator structure for detecting abnormal brain tissues. The proposed biosensor utilizes the photonic band gap property of photonic crystals to control the propagation of electromagnetic waves. By introducing ring resonator cavities within the photonic crystal lattice, strong optical confinement and improved resonance characteristics were achieved. The sensor operates based on the variation of refractive index values of different brain tissues. Simulation results demonstrated that changes in the refractive index cause a measurable shift in the resonant wavelength of the biosensor. The obtained resonant wavelength and transmission characteristics confirm the high sensitivity of the proposed design. The quality factor and output efficiency of the sensor indicate reliable optical performance. The proposed structure is compact and suitable for integration in biomedical sensing systems. The results show that different brain tissues produce distinct resonance shifts, which allows accurate tissue identification. This capability is particularly useful in minimally invasive surgical procedures where real-time tissue identification is required. In addition, the photonic crystal structure provides immunity to electromagnetic interference and enables precise optical sensing. The sensor design can also be extended for detecting other biological parameters. Therefore, the proposed biosensor provides a promising solution for biomedical diagnostics and optical sensing applications. Future work may focus on improving sensitivity and developing practical fabrication techniques for real-time medical applications. Further optimization of the photonic crystal structure can enhance sensing accuracy and response speed. Additionally, integrating the biosensor with advanced medical devices may enable real-time monitoring and improved diagnostic capabilities.

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