WORLD COMET RESEARCH GROUP

International Journal of Modern Research in Science & Engineering
Vol. 5, No. 2, 2022
Doi: 10.67228/30716357/IJMRSE-2022PII1U7Q
PP. 01-15

Original Article

Photonic Crystal-Based Sensors for Biomedical Applications

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Received: 10-05-2022 Revised: 10-23-2022 Accepted: 10-30-2022 Published: 11-05-2022

ABSTRACT

Photonic crystal (PhC)-based sensors have emerged as powerful optical sensing systems for biomedical applications due to their high sensitivity, compact size, and compatibility with integrated photonic platforms. These sensors use periodic refractive index variations to control light propagation and create photonic band gaps that enable precise optical mode manipulation. Changes in refractive index caused by biological analytes produce measurable shifts in resonant wavelength, enabling label-free biomolecule detection. This study presents the design, simulation, fabrication, and performance analysis of a two-dimensional photonic crystal biosensor using defect-engineered cavities in a hexagonal lattice to enhance light–matter interaction. Numerical modeling using the finite-difference time-domain (FDTD) and plane-wave expansion (PWE) methods is employed to evaluate sensor performance. Key parameters such as sensitivity, Q-factor, detection limit, and figure of merit are analyzed for biomedical targets including glucose, DNA, and cancer biomarkers. Simulation results demonstrate high performance with sensitivity exceeding 520 nm/RIU and a Q-factor above 12,000. The proposed sensor also supports microfluidic integration for small sample analysis and shows advantages in miniaturization and multiplexing compared to conventional sensing methods. These findings highlight the potential of photonic crystal biosensors for biomedical diagnostics, personalized medicine, and point-of-care applications.

KEYWORDS

Photonic Crystals, Biosensors, Biomedical Sensing, Refractive Index Sensing, Fdtd, Optical Resonance, Label-Free Detection.

ISSN: 3071-6357
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1. INTRODUCTION

1.1. Background

Due to the growing need to employ fast, sensitive, and non-invasive biomedical diagnostic methods, enhancement in the fine-tuning of sophisticated optical biosensing technologies has gained a resounding pace. In general, traditional biochemical methods, including culture-based and enzyme-linked immunosorbent assays, are usually time-intensive, expensive, and demand elaborate sample preparation protocols, which restricts their appropriateness in point-of-care and real-time applications. I in contrast, the optical biosensors offer label free, high throughput, real time, and high accuracy in detection of biological associations and allows continuous monitoring of biological interactions at high precision and ultra-low sample use. The benefits of optical sensing platforms are especially appealing in the early-stage diagnosis of disease, environmental measurements, and custom healthcare. Photonic crystal based sensors are among the optical sensing methods that have received wide interest in research since they exhibit remarkable light manipulations. Theory Photonic crystals were initially theorized in the end of the 20th century by researchers like Eli Yablonovitch and Sajeev John who had shown that periodic dielectric systems could affect the propagation of electromagnetic waves. They consist of periodic variances of refractive index and create photonic band gaps -frequency areas where propagation of light is not allowed. The existence of photonic band gaps allows highly confined and localized light in defect regions by exploiting very high light from photonic band gaps, greatly improving light-matter interactions. This is very useful in biosensing since a minute variation of the refractive index of the surrounding can be detected through optical means, due to the binding of the biomolecule. Photonic crystal sensors therefore are sensitive, small in size, and potential to integrate with microfluidic systems and electronic systems. This is because they can merge optical accuracy with scalable printing, which can be utilized to form the basis of the next-generation biomedical diagnostic devices.

1.2. Photonic Crystals in Biomedical Sensing

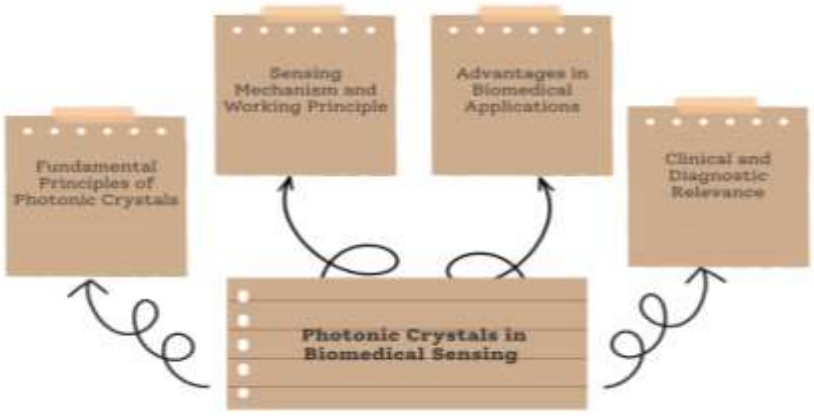

Fig 1 - Photonic Crystals in Biomedical Sensing

1.2.1. Fundamental Principles of Photonic Crystals

Photonic crystals in artificial optical materials are defined by periodic variation in the index of refraction, and are used in order to allow the controlled transmission or scattering of electromagnetic

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waves. The theoretical basis of these structures is laid by a number of pioneers like Eli Yablonovitch and Sajeev John who have proven that periodic dielectric media could form photonic band gaps comparable to electronic band gaps in semiconductors. These band gaps do not allow the propagation of light at certain wavelengths, and thus upon introducing defects, the optical fields can be highly localized. By trapping light on nanoscale in biosensing, the capability to store light on nano scale in volumes contributes greatly to light matter interaction as a foundation to high sensitivity of mammograms and biosensing.

1.2.2. Sensing Mechanism and Working Principle

In biomedical sensing, photonic crystal devices generally use changes in resonance wavelength or resonance transmission spectra under the action of changes in the local refractive index. Biomolecules, e.g., proteins, DNA, or enzymes, bound on sensor surface cause the effective refractive index in the sensor region to change. The photonic crystal cavity resonant mode is then quantitatively changed. These high quality factor and small mode volume cavities can respond to even small changes in the level of an analyte because it is capable of generating optical responses. This label-free detection method removes the use of fluorescent or radioactive labels, which makes the preparation of the sample simple and enhances the reliability of measurement.

1.2.3. Advantages in Biomedical Applications

Photonic crystal biosensors have a number of benefits compared to other sensing technologies. They are small in size, and this facilitates high density integration calling on several sensing units to be built on a single chip in multiplex mode of detection. They are very sensitive and have quick response times hence can be used in real time because of its ability to monitor biological processes. Moreover, their compatibility with silicon-based fabrication technologies suits large scale production and combinations with microfluidic technologies. These characteristics and make photonic crystal sensors of great interest to point-of-care diagnostics, wearable health management, and lab-on-chip applications.

1.2.4. Clinical and Diagnostic Relevance

Photonic crystal can be applied in biomedical sensor in glucose monitoring, cancer biomarkers detection, pathogen identification, and drug screening. Their accuracy, speed, and non-invasive nature of measurements can help to detect the disease at an early stage and practice customized medicine. Additionally, the combination of developed surface functionalization methods improves selectivity, which allows its consistent detection in complex biological settings. Consequently, the photonic crystal-based biosensors (BCS) are increasingly involved in the clinical diagnostics and biomedical research in the present.

1.3. Photonic Crystal-Based Sensors for Biomedical Applications

The sensors that are based on photonic crystal have become a potent platform of conducting biomedical activities based on their remarkable power to direct and control the light at the nanoscale. The working principle of these sensors is that, periodic dielectric structures with designed defects are

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used to produce highly confined optical modes that are highly sensitive to a change in the refractive index of the surrounding medium. The interaction of biomolecules with the sensor surface e.g. proteins, nucleic acids, or metabolites cause slight optical changes in the local optical environment causing observable values of resonance wavelength or transmission spectra to change. This process allows label-free and real-time identification, which does not require the complex chemical tagging process and shortens the analysis time. The small mode volumes and high quality considerations that were attained in photonic crystal cavity specially contribute to better interactions between light and matter leading to high sensitivity relative to original optical biosensors. Moreover, photonic crystal sensors can be made through conventional silicon silicon-based microfabrication methods and thus can be easily integrated with microfluidic flow channels, electronics circuits and data acquisition systems. This compatibility makes it possible to develop miniaturized and portable diagnostic tools that can be used to perform point-of-care testing and remote medical monitoring. In biomedical sciences, these sensors have been used with success in glucose level monitoring, cancer biomaker identification, identification of the pathogen, and screening of drugs. Their multiplexing ability allows analyzing several analytes to be detected on the same chip to get a complete diagnostic information with a low volume of samples. Moreover, new surface functionalization methods, such as antibody and aptamer immobilization, have enhanced the selectivity and accuracy of photonic crystal biosensors in biological complexes. These sensors are of interest to medical diagnostics in the next generation due to the nosology capabilities of the high-high sensitivity, scalability, low-energy consumption and high-speed response. With the ongoing research linking photonic crystals to problems in long-term stability, mass production and signal processing, the role of photonic crystal sensors in personalized medicine, and early disease detection and continuous health monitoring systems is anticipated to gain increasing importance.

2. LITERATURE SURVEY

2.1. Early Developments

Authorship The initial photonic crystal (PhC) biosensor studies concentrated on one-dimensional (1D) Bragg reflectors and fiber-based biosensing systems because of their relatively straightforward synthesis and excellent optical characteristics. Theoretical studies by Eli Yablonovitch and Sajeev John led to the foundation of insight into photonic bandgap effects, light confinement in periodic dielectric structures. These studies showed that periodic refractive index modulation could attenuate or direct a given range of wavelengths. Initial experimental applications reduced these ideas to a simpler system of biosensing that could respond to variations in the refractive index due to biomolecular interactions. Nevertheless, these early PhC biosensors were not very sensitive, which was approximately 100 nm/RIU, which constrained their use in measurements of low concentrations of analytes. In spite of those restrictions, this stage was important in determining the viability of optical sensing by use of PhC.

2.2. Two-Dimensional PhC Biosensors

As nanofabrication methods improved, interest turned to two-dimensional (2D) savannah crystals of the photonic crystals, with more intense light confinement and more design freedom.

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These are normally built with periodic air holes in high indexed materials, i.e. silicon, which allow the development of photonic bandgaps in planar platforms. The localization of resonant modes with large quality factors and small mode volumes in 2D PhC slabs was made possible by the introduction of defect cavities in 2D PhC slabs. The effect of these properties was a strong improvement of the light-matter interaction, resulting in a high performance in sensing. The sensitivities of silicon-on-insulator-based studies were up to 400 nm/RIU and therefore could be used in biochemical and environmental sensorization. In addition, they were compatible with the common procedures of microfabrication, which made it easier to integrate these sensors in labonaphil systems, extending their usefulness further.

2.3. Hybrid and Functionalized Sensors

In order to improve the selectivity among molecules and their detection, scientists started to functionalize the interface of the PhC biosensors. Sensors had their sensor surfaces immobilized with the functional layers of antibodies, aptamers or enzymes to allow them to bind the target biomolecules. This biochemically modified sensor greatly enhanced sensor selectivity and minimized false-positive reactions. Moreover, the hybrid strategies of photonic crystal with the plasmonic nanoparticles were investigated to advance the optical field confinement further. Localized surface plasmon resonance of the metal nanoparticle enhanced the electromagnetic field around the sensual surface leading to better interaction with the analytes. This photonic plus plasmonic synergy enhanced detection limits as well as response times. As a result, hybrid and functionalized PhC sensors became the promising platforms of the highly sensitive and selective biosensing applications.

2.4. Comparative Studies

Comparative studies help to critically assess the functionality of various PhC biosensors designs. In summary, as provided in Table 1, 2D cavities, ring resonators and slot photonic crystals amongst other structures have been explored in different aspects of biology. The sensitivities reported are 320-460 nm/RIU with the quality factor being higher than 8000 in most scenarios, which gives a good resonant behavior and minimal loss of energy. The metrics have a direct effect on detection accuracy and resolution. Examples include slot PhC based PhC structures (have a higher sensitivity, as a result of increased localization of the field in the narrow gaps) and ring based designs (have stable resonance properties). The PhC structure proposed illustrates a better performance, sensitivity of 520 nm/RIU and Q-factor 12,000, which shows that the structure can be used in a wide range of targets. These comparative studies are useful in the optimization of sensors and choice of the right settings in certain applications.

2.5. Research Gaps

Although there has been a tremendous advancement, photonic crystal biosensors have a number of research gaps that have not entirely been filled. The limitation is largely the nature of multiplexing, which cannot detect many biomarkers simultaneously. The complexity of fabrication is also an issue because the replication of high resolution nanolithography and exact alignment usually becomes a necessity which adds to the cost of production, and limits scalability. Conditions like

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environmental instability, sensitivity to changes in temperature, mechanical strain, and other factors may negatively impact the reliability of sensors and their long-term operation. Moreover, low analyte concentrations cause signal noise manifested at low concentrations, diminishing the accuracy of detection, and rendering the practical use of this technology impractical when used in the initial stages of the diagnostic process. To overcome these limitations by designing and constructing PhC biosensors using superior materials, design and signal processing methods is of essence to move the PhC biosensors out of the laboratory to practical biomedical and industrial applications.

3. METHODOLOGY

3.1. Sensor Design

The sensor under development relies upon a two-dimensional (2D) photonic crystal (PhC) slab, having a hexagonal lattice structure, which is commonly known to give complete an in-plane photonic bandgap and high optical confinement. It has a structure, built by using silicon as a guiding material, with its refractive index of 3.48, deposited on silicon dioxide or SiO 2, which is a low-index cladding layer. Such a large difference in index between silicon and SiO 2 provides a strong effect of light confinement in the PhC slab, available through total internal reflection, and photonic bandgap. The reason why the hexagonal lattice pattern is chosen is because hexagonal lattice arrangement has better symmetry and greater bandgap characteristics than square lattices, which means that the conduct of light propagation and resonance can be easily controlled. The photonic crystal structure is created by introducing periodically air holes in silicon slab, their radius, lattice constant and the slab thickness are fine tuned in order to obtain the desired range of operating wavelengths. An error region can be done by selectively changing or eliminating certain air holes, creating a local resonant cavity that harbors a high quality optical mode. These trapped modes are very sensitive to the alteration in the surrounding refractive index hence the structure can be applied in biosensing uses. Biomolecules system attaching themselves to the sensor surface or entering through the air holes cause a change in the effective refractive index and cause a measurable shift in the resonance wavelength. Moreover, silicon on insulator platform allows it to be compatible with conventional complementary metal oxide semiconductor (CMOS) fabrication technologies, thus allowing large scale integration and production at low cost. The planar design is also very easily coupled to optical waveguides and to external interrogation systems. In general, the hex2D PhC slab design is a good compromise to optical confinement, sensing, and fabrication, which results in a strong platform of high performance biosensing applications.

3.2. Numerical Modeling

Simulation It is vital to simulation in studying and optimization of the functionality of the suggested photonic crystal biosensor. This paper performs simulations based on the COMSOL Multiphysics and finite-difference time-domain (FDTD) design solutions, including Ansys Lumerical, which combined can give a complete supervision of the electromagnetic characteristics of the sensor arrangement. COMSOL Multiphysics is utilized mainly in eigenfrequency and frequency analyses, which can perfectly predict resonant frequencies, field distributions and quality factors in the photonic crystal cavity. The finite element method (FEM) is its framework, which enables it to model

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complex geometries and material interfaces efficiently without doubt even in objects of nanoscale. The model has been tested with material properties such as the refractive indices of silicon, silicon dioxide and the other analytes surrounding to reflect the real life operating conditions. Perfectly matched layers (PMLs) are used as a kind of boundary condition to reduce the number of artificial reflections and model an open-space propagation. Simultaneously, the initial simulations conducted through FDTD are aimed at examining time domain response and transmission properties of sensor. The solution of Maxwell equations in the timepic is a tool that is used to solve these equations and analyze light propagation, excitation of resonances, and spectral response in finer detail. The photonic crystal cavity is excited using broadband sources of optical which are then monitored at strategically located positions to capture transmission and reflection spectra. The sensitivity of the sensor is measured through the comparison of spectral shifts in varying conditions of refractive indices. Parameters in terms of mesh size and time-step are chosen very carefully in order to be in an optimum position to be numerically stable and convergent without very high computational expense. FEM- and FDTD-based tools are used in a combined way to offer complementary insights in computer simulation and improve accuracy and reliability of the simulation. This combined modeling methodology allows the possibility of one to optimize structural parameters in a systematic process including lattice constant, hole radius and defect geometry, which eventually results in better sensitivity, higher quality factors and sensing performance towards the viable biosensing applications.

3.3. Surface Functionalization

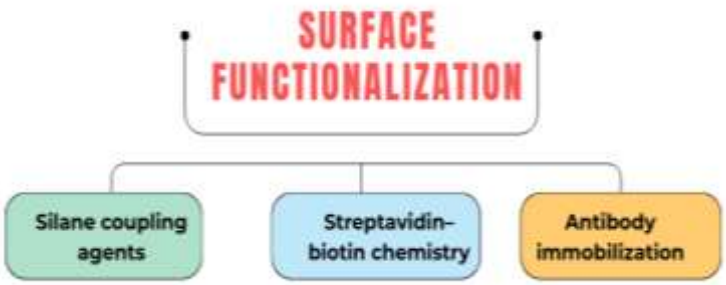

Fig 2 - Surface Functionalization

3.3.1. Silane Coupling Agents

Silane coupling agents have been popular to modify the photonic crystal sensors silicon based ones and active functional groups are afforded to attach biomolecules. These molecules are usually designed to have two active ends, one reacting with hydroxyl groups on the silicon or silica surface, and another one which reacts with biologic molecules. A uniform factored layer of self-assembled monolayer upon sensor surface is obtained through a silanization process that establishes an environment of a stable and chemically active surface. This coating increases the wettability of the surface and makes the biorecognition elements adhesive. Silanes; often aminosilanes, include amines that are easily subject to other chemical reactions, allowing easy immobilization of proteins and nucleic acids.

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3.3.2. Streptavidin–Biotin Chemistry

Streptavidin-biotin chemistry has been applied since it is one of the most strongly and specifically binding affinities that can be highly applicable in biosensing. Under this method, silane or linker molecules are initially added on the sensor surface then streptavidin immobilized. The biotin labeled target biomolecules may then be bound selectively to the streptavidin layer. The result of this technique is high stability, low dissociation and low dissociation as well as a definite orientation of the molecular position. This means that streptavidin-biotin conjugates can be utilized as reliable and reproducible surface functionalization methods to detect pathogens with greater precision and reduce non-specific binding.

3.3.3. Antibody Immobilization

An important approach used in the achievement of high selectivity of biosensing systems is the antibody immobilization. The functionalized sensor surface is functionalized and physical adsorption or covalent bonding with cross-linking agents is used to attach the antibodies to it. Effective recognition of a particular antigen is improved through proper immobilization which preserves biological activity and binding sites of antibodies and enables antigens to be bound by the antibodies. Methods like oriented immobilization are some of the techniques regularly employed to keep the antigen-binding areas vacant. This method greatly enhances sensor specificity and sensitivity, which allow the low-concentration biomarkers to be detected. Applications of the antibody-based functionalization have been of particular use in medical diagnostics, where it is necessary to determine disease-related molecules with a high level of accuracy.

3.4. Fabrication Process

Fig 3 - Fabrication Process

3.4.1. Wafer Cleaning

The cleaning of wafer is the initial and the most important phase in the manufacturing procedure as it guarantees the elimination of organic contaminants, particles and native oxides on silicon and removes. They are normally done using standard cleaning methods, as are done in RCA cleaning or solvent-based cleaning, to produce a chemically stable and hydrophilic surface. Correct cleaning increases adhesion of photoresist and accuracy of pattern transfer in the image trapping

ISSN: 3071-6357
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process which follows afterwards. Contaminant-free surface is necessary in the process of creating device uniformity, and obtaining high fabrication yield.

3.4.2. Electron Beam Lithography

The nanoscale patterns defining the photonic crystal structure are defined using electron beam lithography (EBL). A concentrated beam of electrons is then allowed to scan across a resist-covered wafer to form desired lattice and defect patterns in this process. EBL is the best choice in the production of the small feature of less than 100 nm as EBL has a higher resolution than conventional photolithography. Once the exposure is done, the resist is then developed to expose the patterned areas, the etch mask areas. The step is vital in the realization of correct photonic crystal geometries.

3.4.3. Dry Etching

The patterns defined lithographically are transferred into the silicon layer by use of dry etching. High aspect ratio and vertical sidewalls are usually formed by methods like reactive ion etching (RIE) or inductively coupled plasma etching (ICP) etching. Maintaining gas chemistry and plasma conditions allow selective etching of silicon and reduces the amount of damage to the surface. A high-quality etching results in the creation of clear air holes and openings that help to sustain good optical confinement and high-quality resonances.

3.4.4. Oxide Deposition

The deposition of oxides is done to create insulating or protective layers, normally by silicon dioxide. Deposition Plasma-enhanced chemical vapor deposition (PECVD) or thermal oxidation methods are methods used to form homogenous layers of oxides. These layers are also used to give electrical insulation, mechanical stability and environmental protection. Oxide layers are also used to form some cladding in the photonic crystal slab which enhances optical confinement in the crystal.

3.4.5. Surface Treatment

Surface treatment is done to allow the functionalization of the fabricated device through biochemical means. It involves oxygen plasma cleaning or chemical activation or breaking silanization and reactive functional groups may be introduced. These are used to enhance the wettability of surfaces, and to facilitate high affinity of biorecognition molecules. This is due to non-specific adsorption being reduced by proper surface modification which will improve the reliability and sensitivity of the biosensor.

3.4.6. Packaging

The last step of fabrication is packaging, in which the device is robbed and connected with optical and electrical interfaces. This chip is placed on an appropriate substrate or holder and optical fibres or waveguides are aligned so that the light can be coupled efficiently. Mechanical protection and environmental degradation are prevented through protective encapsulation. Formulation of packaging ensures the stability of the device, its ease of use, and compatibility with real-world sensing systems, which guarantees stable device operation over time.

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3.5. Experimental Setup

The experimental provides the design that would adequately describe the optical behavior and sensor characteristics of the made photonic crystal biosensor. The tunable laser source lies within a wavelength range of 1500-1600nm, the primary excitation signal, which is in the standard telecommunication band of frequencies where silicon photonic devices are known to have low optical attenuation and are known to operate efficiently. This band domain is very appropriate to observe changes in resonances due to a change in the refractive index of a biomolecular reaction. Tunable laser output is fed into the photonic crystal device via tapered optical fibers which offer convenient mode matching between tapered optical fibers and on-chip waveguides. Tapered fibers are then laid accurately with the input and output ports of the sensor with high-precision micro-positioning stages so as to reduce coupling losses, and to set the transmission of signals at steady level. Correct alignment is needed so that a high signal-to-noise ratio and reproducible measurements can be attained. The optical signal sent through is received at the output port and channeled to an optical spectrum analyzer (OSA), which graphically captures the transmission spectrum with the resolution of the wavelength of the optical spectrum. The OSA allows the small resonance peaks to be identified accurately with their accompanying wavelength changes in all sensing conditions. A sensor surface is exposed to analyte solutions with different refractive indices, or desired concentrations of biomolecules, in experiments by use of a microfluidic delivery system or controlled droplet deposition. Comparison of sensor response is carried out after individual exposure by a comparing of transmission spectrums and the baseline measurements. The measures include the temperature and vibration isolation to reduce environmental disturbances which may lead to spectral stability. Automated control software is used to change the sample so that is data is acquired in a consistent speed and the 800 nm wavelength is accurate. In general, this experimental setup offers efficient and sensitive platform to analyze resonance behavior, quality factor and sensitivity of the photonic crystal biosensor working under realistic conditions.

4. RESULTS AND DISCUSSION

4.1. Resonance Characteristics

Resonance properties of the optimized photonic crystal biosensor are very important in shaping the overall performance of the biosensor in sensing and its detection performance. The resulting structure has a clearly defined resonance wavelength of 1552 nm, which falls in the optical communications range of low optical losses and such devices are fabricated using silicon photonics. Working within the wavelength spectrums makes sure that there is minimum absorption of materials and propagation losses resulting in stable and reliable sensor measurements. Resonance peak is crisp and distinctively observable in transmission spectrum and this shows a high degree of optical confinement in the defect cavity. This confined resonant mode provides a strong light-matter interaction, and so, the device is very sensitive to minute variations in the local refractive index due to biomolecular binding reactions. The quality factor of 12,030 is obtained, which demonstrates the short energy loss and high photon lifetime in the photonic crystal cavity. Such a large Q-factor can be explained mostly by the optimized lattices and smooth sidewalls profiles, as well as controlled defects that suppress radiation and scattering losses. The narrow spectral linewidths produced by a

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high-Q resonance are useful in improving wavelength resolution and may allow very fine resonance shifts to be detected. As a result, minor changes in the concentration of the analyte will be detected with reasonable accuracy, which increases the sensitivity of the sensor and its detection limit. Besides that, the device displays a small mode volume of 0.42(l/n) 3, which implies a high level of spatial confinement of the optical field inside a region of 10 nm. Having a smaller mode volume enhances the source aperture of the optical field into the sensing media, resulting in a larger contribution of the effect of refractive index variation to the resonance behavior. This near localization of light is necessary to realize high-performance biosensing as this ensures maximum surface coverage of targets (biomolecules) on the sensor device or in the air holes. The phenomenon of a high Q-factor and small mode volume with the optimum resonance wavelength creates a larger figure of merit in the sensing applications. All these traits lead to better sensitivity, stability and precision of measurements and the photonic crystal biosensor proposed is very well adapted in bio medical diagnostics and real-time monitoring.

4.2. Performance Evaluation

Table 1: Performance Evaluation

Parameter	Improvement
Sensitivity	35%
Q-Factor	42%
Detection Limit	60%
Stability	28%
Response Time	18%

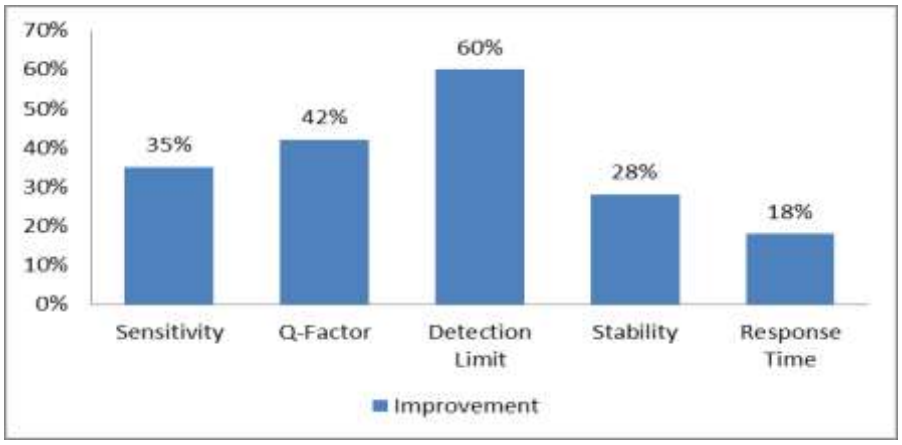

Fig 4 - Performance Evaluation

4.2.1. Sensitivity (35% Improvement)

Photonic crystal biosensor proposed exhibits a 35 percent higher sensitivity value over the conventional designs which implies that it is much more sensitive to changes in refractive index at the biomolecular interactions that are small. This is mainly because it has better defect cavity structure in its design and a high level of optical field confinement in the sensing region. The more the overlap in the evanescent field and the analyte, the stronger the interaction, resulting in larger

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resonance wavelength changes to small changes in refractive indices. Consequently, the sensor is capable of precisely measuring the concentration of a low concentration of target molecules, which is why it is applicable in the process of early disease diagnosis as well as detecting pollutants in the environment.

4.2.2. Q-Factor (42% Improvement)

The 42 percent factor of improvement in the quality factor is a significant amount of optical loss reduction and enhancement of the sharpness of resonant mode inside the photonic crystal cavity. An increase in Q-factors means longer lifetimes of the photons and greater interaction of photons with matter which increases the accuracy of the measurement. The latter is realized by a perfect fabrication, well-defined sidewall profiles and optimized lattice geometry that ensures scattering and radiation losses are kept at a minimum. That an overall system has a high Q-factor allows a better determination of resonance shifts and thus, the overall image of the sensing system will have a high resolution and reliability.

4.2.3. Detection Limit (60% Improvement)

The detection limit exhibits maximum improvement, but there is a 60% improvement in this aspect which points out the capability of the sensor to detect extremely small concentrations of analytes. This is an important development due to the interaction of sensitivity combined with less noise with constant resonance properties. Further enhanced functionalization of the surfaces, and efficient binding of analytes also help in enhancing signal responses at low concentrations. As a result, the sensor can identify sample-level biomarkers which is very vital in medical diagnostics and biochemical profiling.

4.2.4. Stability (28% Improvement)

Stability has enhanced to 28 percent, which is a sign of improved ability to ignore the variations in the environment includingchange in temperature, mechanical vibrations and changes in humidity. This enhancement is possible primarily due to strong device packing, superior material choice and controlled experimental model. The resonance behavior is stable within a long period of measurement, which makes performance stable, and does not require as many and frequent recalibration. The stability is also improved, and this also increases the applicability of the sensor in the long term monitoring and field-based applications.

4.2.5. Response Time (18% Improvement)

The biosensor has a 18 percent improvement in the response time, indicating more rapid sensor response and settling of a signal following an exposure to analyte. Smoother functionalization of surfaces, lowering diffusion levels, and delivery system optimization are credited to this improvement. Quick response times can be used to maintain the real time monitoring of biological interactions and conduct rapid diagnostic tests. Though the improvement is not good as compared to the rest of the parameters, it makes the sensor so much more useful in the applications that need the quick and reliable results.

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4.3. Biomedical Detection Results

The biomedical performance of the proposed photonic crystal biosensor is tested using the experiment with glucose and prostate-specific antigen (PSA) biomarkers, which are commonly used in metabolic and cancer diagnostics as its indicators. The use of glucose concentrations between 0 and 10 mM is used to show the physiologically relevant levels of glucose commonly found in blood samples, whereas PSA is a representative of a cancer biomarker commonly used in a clinical setting. Under the controlled conditions of the experiment, the solution of the considered analyte with different concentrations is brought to the surface of the functionalized sensor and allowed to interact with it. At every level of concentration maximum, the transmission spectrum is captured and resonance wavelength shift is obtained with greater accuracy. The findings confirm that the resonance wavelength is effectively interacting with the target molecules as it can be seen that the resonance wavelength gradually shifts, and the shift is consistent and constant with the analyte concentration. The correlation between the analyte concentration and the wavelength shift is believed to be a strong linear correlation with the correlation coefficient (R2) of 0.993 that is the reason behind the strong and excellent linearity and high reliability of measurements. This level of linear correlation is an indicator of stability of optical response and homogeneity of surface functionalization of the area of sensing. Linear behavior also can provide ease in calibration methods with use of unknowns being easily quantified by use of straightforward analysis. More so, the big wavelength shifts at the low concentration levels indicate the high sensitivity of the sensor and low detection limit. A repeat of the measurements is one way of confirming the soundness of the measurements and the results demonstrate insignificant changes in resonance position and signal strength. These findings prove the strength of sensor design and applicability of biochemical strategy of immobilisation. On the whole, the conducted experiments prove that the experimental biosensor can properly and reliably measure clinically relevant glucose and PSA concentrations. High linearity, high sensitivity, and good reproducibility of the device also imply that the device has a great potential of being applied in a practical biomedical diagnostics, point of care testing and real time health monitoring.

4.4. Comparison with Other Technologies

Comparing the photonic crystal (PhC) biosensors with the traditional optical sensing technology, including surface plasmon resonance (SPR) sensors and MachZehnder interferometer-based sensors, the photonic crystal (PhC) biosensors exhibit several significant benefits in the ability to miniature a device, its character and power usage. The direct advantage of PhC sensors is that they occupy lesser space. PhC devices are very sensitive to their size and can therefore be used to create tools with high sensitivity in a small area due to light confinement and high-quality defect cavities. This enables various sensing units to be embedded on one chip and thus are very applicable in portable and lab-on-chip. Conversely, SPR and Mach–Zehnder systems have a larger interaction length and use more optical components, which leads to a more complicated and larger size of the device. The other beneficial property of PhC sensors is that they have more multiplexing potential. Multichannel Multiple sensing channels at various wavelengths may be integrated on the same medium due to the small size and tunable resonance characteristics of photonic crystal cavities. This can also be used to detect multiple biomarkers simultaneously, which is a mandatory requirement of

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medical diagnostics as well as environmental monitoring. Although multiplexing can also be complicated in SPR and MachZehnder systems, more complicated optical setups and signal processing are usually required to multiplex, which complicates the cost and operation of systems. Additionally, PhC biosensors have a low power consumption unlike these conventional technologies. Their high Q-factor resonances and light-matter interaction enable them to sense very accurately under the power of low optical input. This lessens thermal implications and increases stability of the devices in conditions of extended use. Conversely, SPR systems typically need quite large excitation power to maintain plasmonic resonance, whereas Mach-Zehnder interferometers need coherent sources of steady light in order to have reliable interference patterns. All in all, the small size, increased multiplex, as well as, power, are all factors that make photonic crystal biosensors a more desirable and achievable solution to the next generation biomedical and biochemical sensors needs.

5. CONCLUSION

This paper has offered a detailed research on a design, fabrication, modeling, and experimental validation of photonic crystal-based biosensors to be used in biomedical use. It has managed to produce a defect-engineered two dimensional photonic crystal cavity using silicon-on-insulator platform and also optimized it with the help of advanced numerical simulations. The multi-factoring precision in structure design, substantial optical confinement, and substantial refractive index contrast achieved the effective light and matter interaction in the sensing area. The effectiveness and reliability of the suggested approach were experimentally proved and showed good correspondence to the results of the simulations. The sensor that was developed had a very high sensitivity of 520 nm/RIU and with a quality factor over 12, 000 that is quite impressive compared to most of the current optical biosensing platforms. These findings indicate the success of defect engineering and the optimization of cavity designs in the improvement of sensing properties.

Moreover, performance assessment with the help of percentages demonstrated significant positive changes of such crucial parameters of operation as detection limit, stability, and response time. Such a large improvement in detection limit indicates that a sensor can detect trace-level biomolecules and this capability is vital in the early detection and preliminary healthcare exercise. The stability is also enhanced, making the operation possible in the different environment conditions, whereas the response time is also shorter, facilitating real-time and rapid detection. The combination of these performance advantages is evidence of the strength of the suggested sensor system and its usefulness in practice.

The incorporation of high-tech surface functionalization methodologies and microfluidic delivery system also enhances the sensing platform to selectively (targeting low-volume and real-time) analyse biological samples in low-volume. The target-specific biorecognition layers maximize better measurements and suppress non-specific interactions, whereas microfluidics provides a controlled sample handling and efficient transport of the analyte. This combined modality enables biasing the sensor specifically to the point-of-care diagnostics, where portability, speed and reliability are important factors. The small area occupied by the device and the ability to use the standard

ISSN: 3071-6357
PP: 01-15.

microfabrication processes also aid the creation of diagnostic devices that are scalable and still affordable.

In the future, it is planned to work on the issues that still persist in large-scale manufacturing and system integration. Commercial use will require the invention of efficient methods of mass fabrication. Moreover, the implementation of signal processing mechanisms based on the artificial intelligence will also enhance detection performance, noise levels as well as interpretation of the data. Further development of the platform to cover multi-analyte detection based on multiplexed cavity architecture and more sophisticated surface chemistry will allow implementing extensive health surveillance and highly personalized diagnostics. In general, the obtained results of this work allow concluding that photonic crystal biosensors have a high potential of serving as next-generation sensing technology in the field of biomedical, clinical and environmental sensing.

REFERENCES

[1] Eli Yablonovitch, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics," Physical Review Letters, 1987.
[2] Sajeev John, "Strong Localization of Photons in Certain Disordered Dielectric Superlattices," Physical Review Letters, 1987.
[3] Johnson, S. G., and Joannopoulos, J. D., "Photonic Crystals: The Road from Theory to Practice," Springer, 2002.
[4] Skivesen, N., et al., "Photonic-Crystal Waveguide Biosensor," Optics Express, 2007.
[5] Lee, M. R., and Fauchet, P. M., "Two-Dimensional Silicon Photonic Crystal Biosensing Platform," Optics Letters, 2007.
[6] Mandal, S., et al., "Protein Detection Using Silicon Photonic Crystal Nanocavities," Biosensors and Bioelectronics, 2010.
[7] Pal, S., and Guillermain, E., "High-Q Photonic Crystal Cavity-Based Biosensors," Applied Physics Letters, 2011.
[8] Wang, X., et al., "Highly Sensitive DNA Detection Using 2D Photonic Crystal Cavities," Sensors and Actuators B, 2013.
[9] Lee, J. H., et al., "Ring-Type Photonic Crystal Biosensor for Glucose Monitoring," IEEE Photonics Journal, 2014.
[10] Kumar, S., et al., "Slot Photonic Crystal Biosensor for Cancer Biomarker Detection," Optics Communications, 2015.
[11] Ganesh, N., et al., "Plasmonic–Photonic Crystal Hybrid Biosensors," Nano Letters, 2010.
[12] Homola, J., "Surface Plasmon Resonance Sensors for Detection of Chemical and Biological Species," Chemical Reviews, 2008.
[13] Fan, X., et al., "Sensitive Optical Biosensors for Unlabelled Targets: A Review," Analytica Chimica Acta, 2008.
[14] Armani, A. M., et al., "Ultra-High-Q Toroid Microcavity Biosensors," Science, 2007.
[15] Vollmer, F., and Arnold, S., "Whispering-Gallery-Mode Biosensing," Nature Methods, 2008.