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**INVESTIGATION OF ENHANCED SENSITIVITY IN TWO-DIMENSIONAL
PHOTONIC CRYSTAL SENSOR PLATFORMS FOR APPLICATION IN CLINICAL
DIAGNOSTICS**

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

((فَرَحِينْ بِمَا آتَاهُمُ اللَّهُ مِنْ فَضْلِهِ

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Table of Contents

General Introduction.....	1
Chapter I: Fundamentals of Photonic Crystals and Optical Sensing	
I.1. Introduction	5
I.2. History	5
I.3. Photonic crystal (Phc).....	6
I.3.1. Photonic Band gap.....	7
I.3.2. Two dimensional photonic crystals (CPs .2D).....	10
I.4. Principles of Optical Sensing.....	13
I.4.1. Refractive Index Sensing Mechanism.....	13
I.4.2. Wavelength Shift vs. Intensity Interrogation.....	14
I.4.3. Key Performance Metrics: Sensitivity, Q.factor, Limit of Detection (LoD).....	14
I.5. Simulation Framework.....	15
I.5.1. Plane Wave Expansion	16
I.5.2. 2D Finite.Difference Time.Domain (FDTD).....	17
I.5.3. Polarization of the electromagnetic wave (TE and TM)	18
I.5.4. Photonic bandgap analysis using RSOFTE Simulator	18
I.6. Conclusion.....	20
Bibliographic references of Chapter 01.....	21
Chapter II: State of the Art and Photonic Crystal Sensor Architectures	
I.1. Introduction	27
I.2. Photonic Crystal Sensors	28
I.3. State of the Art in Photonic Crystal Biosensors.....	28
I.3.1. Historical Development of Photonic Crystal Sensors.....	29
I.3.2. Critical Review of Reported Sensitivity Limits (nm/RIU and LoD).....	29
I.4. 2D Photonic Crystal sensor Architectures	31
I.4.1. Sensor based on Photonic Crystal Slabs and Membranes	31
I.4.2. Sensor Based on Photonic Crystal Nanocavities	34
I.4.3. Sensor Based on Slot-Photonic Crystal Waveguides.....	36
I.5. Identified Research Gaps and Contribution of This Work.....	38
I.6. Conclusion.....	39
Bibliographic references of Chapter 02.....	40

Chapter III: Design and Numerical Modeling of the Two-Dimensional Photonic Crystal Biosensor

III.1. Introduction	42
III.2. Design of the Two-Dimensional Photonic Crystal Structure.....	42
III.3 Design Parameter Optimization.....	43
III.4 Photonic Crystal Cavity Configuration: Structures with and without Ring Cavity.....	44
III.4.1 Photonic Crystal Structure without Ring Cavity.....	44
III.4.2 Photonic Crystal Structure with Ring Cavity.....	45
III.4.3 Effect of Ring Cavity Inner Radius (R_{in}) on the Performance of the Proposed Biosensor... ..	46
III.4.4 Effect of Ring Cavity Outer Radius (R_{out}) on the Performance of the Proposed Biosensor.....	48
III.5 Sensing Mechanism for Early Vitiligo Detection.....	49
III.6. Conclusion.....	53
Bibliographic references of Chapter 03.....	54
General Conclusion	55

List of Figures

Figure I.1 : One, two and three dimensional photonic crystals.....	6
Figure I.2: Band structure in a two dimension photonic crystal lattice.....	8
Figure I.3 : Connected 2D periodic structure.....	11
Figure I.4 : Disconnected 2D periodic structure.....	11
Figure I.5: Examples of simple one-time defects.....	12
Figure I.6 : Examples of linear defects in a photonic crystal created.....	12
Figure I.7: The sensing performance of an optical RI sensor.....	13
Figure I.8 : The transmission is function of wavelength with varying of refractive index.....	14
Figure I.9: Transverse magnetic TM and transverse electric TE polarization.....	18
Figure I.10: The diagram of the hexagonal structure used for the biosensor design is based on 2D-Photonic crystal.....	19
Figure I.10 : Presents a diagram of photonic bandgaps of the PhC hexagonal structure.....	20
Figure II.1 : The photonic sensing technologies based on (a) optical WG, (b) Optical Fiber (c) Meta surface , (d) Photonic Crystal , and (e) plasmonics.....	28
Figure II.2: Schematic of photonic crystal slab (PCS).....	31
Figure II.3 : The association of first 90.0 nM CD40 ligand antibodies (150 kDa), second 90.0 nM EGF antibodies (150 kDa) and third 500 nM streptavidin (60 kDa) all dissolved in DPBS is observed in the normalized intensities of the transmitted light, while no unspecific binding events are visible in the signal sequence.....	32
Figure II.4: (Color online) Schematics of the liquid/SiNx/air suspended membrane design.....	33
Figure II.5: (Color online) Sensitivity evaluation of CPCS TM and TE like GR modes with same parameters.....	33
Figure II.6 : Photonic crystal nanocavity sensor.....	34
Figure II.7 : Structural design diagram of the 2-D PhC microcavity gas sensor.....	35
Figure II.8 : (a) Transmission spectra obtained at the waveguide output of the 2-D PhC microcavity sensor (b) wavelength values at the resonant peaks of the transmission spectra for seven gases (including air) and the linear fitting curve corresponding to the refractive index of the gases.....	35

Figure II.9 : (a) Structure of the integrated photonic crystal waveguide and edge-cavity, which are coupled by a micro-cavity within the dashed-rectangular between them. (b) Transmittance to the S2 port versus wavelength around the resonant peak at 1787.7 nm for varying value of air refractive index n_s [16].....37

Figure II.10 : (a) 3D schematic of the 2D PCW with a 220 nm thick Si layer and a 2 μm thick BOX layer. (b) Geometric parameters of the 2D PCW including the lattice constant a , radius of bigger air holes R , radius of center defect holes r_0 , waveguide width $W_{1.1}$, thickness of Si h , and direction of the defect $\Gamma - K$. (c) Dispersion diagram under air and pure C_2H_2 background. (d) Hz distributions of even mode and odd mode (e) $|E|$ distribution of the even mode (f) at the cross section through a defect hole and (g) through Si slab in (e). (h) Guided mode bandwidth below the SiO_2 light line in terms of wavelength (nm). (i) Simulated curves of group index and insertion loss versus the lattice constant. [17].....38

Figure III.1. (a) Layout of the proposed two-dimensional photonic crystal (2D-PhC) structure, (b) Photonic band diagram of the designed 2D-PhC structure.....43

Figure III.2. (a) Structure model of the first biosensor based on a microcavity coupled to two waveguides, where the cavity radius $R=1.2a$. (b) Normalized transmission spectrum for the proposed design for $n=1$ 45

Figure III.3. (a) Structure model of the first biosensor based on a microcavity coupled to two waveguides, where the ring radius $R_{in}=0.21\mu\text{m}$ and $R_{out}=0.41\mu\text{m}$. (b) Normalized transmission spectrum for the proposed design for $n=1$ 46

Figure III.4. The variation of the resonant wavelength and the sensitivity according to the inner radius R_{in} for $R_{out}=0.41\mu\text{m}$ 47

Figure III.5. The variation of the resonant wavelength and the sensitivity according to the outer radius R_{out} for $R_{in}=0.23\mu\text{m}$ 48

Figure III.6. Normalized transmission spectra as a function of wavelength.....52

List of tables

Table II.2 : Summary of reported photonic crystal biosensor performances.....	30
Table III.1. The values of resonant wavelength and sensitivity according to R_{in}	47
Table III.2. The values of resonant wavelength and sensitivity according to R_{out}	49
Table III. 3. Refractive index of normal and affected-vitiligo skin.....	50
Table III. 4. The values of resonant wavelength, Q-factor, and sensitivity for normal and vitiligo-affected skin.....	53

LIST OF ABBREVIATIONS

Abbreviation	Explanation
PC	Photonic Crystal
1D	One dimension
2D	Two dimensions
3D	Three dimensions
PBG	Photonic Band Gap
TM	Magnetic transverse
TE	Transverse Electrical
RI	Refractive index
FDTD	Finite-Difference Time-Domain
PWE	Expansion des ondes planes
SOI	silicon-on-insulator
LOD	Limit of detection.
FoM	figure of merit
CPCS	Colloidal Photonic Crystal Sensor

MATHEMATICAL SYMBOLS AND PARAMETERS

Symbol	Meaning	Unit
λ_0	Resonant wavelength	nm
ω	Angular frequency	rad /s
ν	frequency	Hz
η	Refractive index	RIU
c	Speed of light in vacuum	m/s
r	Radius of air holes	μm
a	Period	μm
S	Sensitivity	nm/RIU
K	the wave vector	$k^{-1}k^{-1}$
Q	Quality factor	-
ε	Dielectric permittivity	-
R_{in}	Inner radius of ring cavity	μm
R_{out}	Outer radius of ring cavity	μm

General Introduction

General Introduction

In recent years, photonic crystals (PhCs) have emerged as a promising platform for integrated optical devices because of their ability to manipulate light through a periodic modulation of the refractive index at the wavelength scale. This periodic structure gives rise to the photonic bandgap (PBG), a frequency range in which light propagation is forbidden. [1,2] The introduction of structural defects, such as point or line defects, into the PhC lattice creates localized modes within the PBG. These defect modes are highly sensitive to variations in the surrounding refractive index, making PhCs excellent candidates for optical sensing applications. Among their biomedical applications, the detection of skin diseases has attracted increasing attention, particularly in the case of vitiligo. [3–5]

Vitiligo is a chronic autoimmune skin disorder characterized by the progressive loss of melanocytes, affecting nearly 0.5–2% of the global population. Although not life-threatening, the disease can cause considerable psychological and social distress. Conventional diagnostic approaches, including visual examination under Wood's lamp and skin biopsy, are often subjective, invasive, and insufficiently sensitive for early diagnosis or monitoring disease progression. Therefore, there is a growing need for rapid, non-invasive, cost-effective, and quantitative diagnostic techniques. In this context, photonic crystal biosensors offer a promising label-free sensing approach for detecting vitiligo.

This study investigates the enhancement of sensitivity in two-dimensional photonic crystal sensor platforms tailored for clinical diagnostic applications, with a specific focus on vitiligo detection. By optimizing key structural parameters—including lattice constant, hole radius, and defect configurations—we aim to achieve ultrahigh sensitivity, a high figure of merit (FOM), and a low detection limit for refractive index changes induced by specific biomolecular interactions. Numerical simulations based on finite-difference time-domain (FDTD) or plane wave expansion (PWE) methods are employed to analyze the band structure and transmission spectra of the proposed PhC designs. The ultimate goal is to develop a novel, compact, and highly sensitive photonic biosensor capable of enabling early diagnosis and therapeutic monitoring of vitiligo, thereby contributing to personalized and point-of-care medical diagnostics.

In this context, this dissertation comprises three chapters:

In the first part, we will explore the fundamentals of photonic crystals and optical sensing. It will focus on tailoring the periodic dielectric architecture to create highly sensitive optical cavities and waveguides. Some key optimization strategies for improving sensitivity, selectivity, quality factor (Q), and the overall figure of merit (FoM) of these nanophotonic sensors will be systematically presented.

The second chapter, we will provide a comprehensive overview of photonic crystal (PhC)-based optical sensors, which have emerged as a powerful platform for label-free biosensing due to their ability to confine light at the nanoscale and enhance light–matter interactions.

In the third part, the proposed structure will be presented, along with the steps to be followed to design a two-dimensional photonic crystal-based biosensor for the detection of vitiligo. The chapter further describes the numerical simulation methods and computational tools used to analyze the optical properties of the proposed biosensor, specifically the optical FDTD software and the PWE solver. Finally, we will discuss the obtained simulation results.

We conclude this thesis with a general conclusion explaining the overall performance of the proposed two-dimensional photonic crystal sensor, discussing its limitations, and suggesting future directions for clinical implementation and point-of-care diagnostics.

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Chapter I:

Fundamentals of Photonic Crystals and Optical Sensing

I.1. Introduction

In this chapter, we explore the fundamentals of photonic crystals and optical sensing. This chapter focuses on tailoring the periodic dielectric architecture to create highly sensitive optical cavities and waveguides. The core principles of band gap engineering, defect mode formation, and resonant field enhancement are examined as the foundation for maximizing light-matter interaction. Key optimization strategies for improving sensitivity, selectivity, quality factor Q , and the overall figure of merit (FoM) of these nanophotonic sensors are systematically presented.

I.2. History

Ho, Chan, and Soukoulis were the first to introduce a method for constructing a dielectric structure with a band gap [1]. This periodic structure, especially in micron and smaller dimensions, with application in infrared and optical devices cannot be easily constructed. Subsequently, Yablonovich proposed a three-dimensional diamond shaped cylindrical structure as the first experimental structure, which was able to support an optical crystal band according to theoretical calculations. Yablonovich also constructed the first PhC in 1991[2-3].

Research continued to find simpler structures in low dimensions, until Lin et al [4] designed a new three dimensional layer structure with a three dimensional band gap in a wide range of structural parameters. For the first time, layer structures in the microwave spectrum were made with aluminum cylinders. However, the difficulty to construct three-dimensional PhCs for optical visible waves caused two other research groups to study the band structure of quasi-2D slabs. The results showed that these structures have a band gap within the surface and, due to the general reflection phenomenon, limit the light in other directions. The main success of the structure was its simple construction method. Subsequently, scientists and researchers proposed different construction methods, which will be referred to below.

Eli Yablonovich and Saghi Jan in 1987 used the «crystal light» term [2]. However, before that, one-dimensional PhCs were studied in detail as a one-dimensional multilayer periodic matter similar to Bragg's mirrors. Lord Rayleigh began his studies in 1887 by showing these structures with a one-dimensional forbidden band[5]. Today, these bands are used in many cases as high reflectivity layers to increase the efficiency of diodes and mirrors with high reflectivity in laser cavities. A detailed theoretical study of PhCs by Vladimir Baikov was

conducted to investigate the effect of the prohibition band on the spontaneous emission of atoms and molecules [6]. Bikov also thought to use periodic two and three-dimensional structures [7]. However, Oehtaka studied the concept of 3D PhC in 1979[8]. The main motive for Yablonovich was to engineer the density of optical states to control spontaneous emission into PhCs, however, John's [9] was to affect the motion and trap the photons. Increasing the studies on PhCs leads to minimize dimension to micrometers and even nanometers suitable for use in computer and optical communications circuits.

I.3. Photonic crystal (PhC)

Since photonic crystals (PhCs), defined as dielectric structures with a periodic modulation of the refractive index, exhibit unique interactions with electromagnetic waves, they have attracted considerable attention in recent years [10]. Their behavior is analogous to that of electrons in semiconductor crystals, which originates from the mathematical similarity between the Schrödinger equation in solid-state physics and the Helmholtz equation in electromagnetism. In this analogy, the refractive index distribution in photonic crystals plays a role similar to the electrical potential in semiconductors, leading to comparable control of photons and electrons, respectively [11,12].

Photonic crystals are classified into one, two, and three-dimensional structures, depending on the periodicity of the refractive index (Figure I.1).

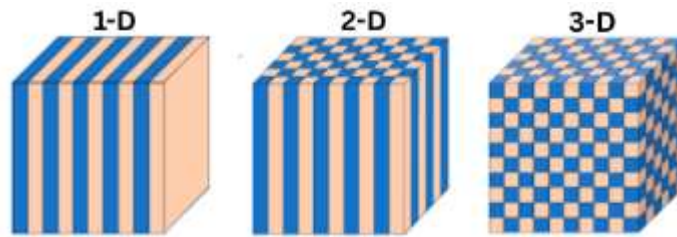


Figure I.1 : One, two and three dimensional photonic crystals [13]

For efficient propagation of electromagnetic waves, a correspondence must exist between the operating wavelength and the geometric dimensions of the photonic crystal. Depending on their periodicity, photonic crystals with millimeter scale and micrometer scale dimensions can be employed to control microwave and infrared waves, respectively [10]. The dispersion relation between frequency and wave vector describes the propagation of waves in

such periodic media. However, in non-homogeneous materials, this dispersion relation becomes complex and strongly depends on the direction of wave propagation within the crystal lattice [14].

One of the most significant consequences of periodicity in photonic crystals is the formation of a photonic band structure. The wavelengths of light that are allowed to propagate are referred to as modes, and these modes form photonic energy bands. In contrast, certain continuous and bounded frequency ranges prohibit wave propagation and are known as photonic band gaps (PBGs) [10], [11]. The width and depth of these band gaps are determined by the lattice geometry, refractive index contrast, and periodicity of the crystal. Due to symmetry considerations, photonic band gaps may appear only along specific crystallographic directions, and they can be determined both theoretically and experimentally in two- and three-dimensional photonic crystals [12], [14].

In practical photonic crystal structures, several factors such as polarization, lattice density, and defects must be considered to tailor the band structure. When the translational symmetry of the periodic lattice is broken by introducing a defect, localized photonic states are formed within the band gap [15]. These defects can be created by modifying the dielectric constant, altering the thickness of a layer, or removing lattice elements. This phenomenon is analogous to impurity states in semiconductors, where additional energy levels appear within the electronic band gap. The type and size of the defect determine the characteristics of the localized modes, including their resonant frequency, polarization, symmetry, and electromagnetic field distribution [16]. Analysis of defect modes through transmission, reflection, and absorption spectra is therefore essential for understanding and optimizing the optical properties of photonic crystals.

Photonic crystals are also widely used to form waveguides, enabling precise control over light propagation at the micro and Nano scale [14]. To analyze and design such structures, various numerical simulation tools are employed, each relying on specific computational techniques. Among these methods, the Plane Wave Method (PWM) is extensively used for photonic band structure calculations [12]. More generally, the interaction between radiation fields and matter—including photon absorption, emission, elastic and inelastic scattering—constitutes a fundamental topic in modern optics and is described using both classical electromagnetism and quantum electrodynamics [11].

The 2D photonic crystal sensors have many advantages in terms of small size and high sensitivity, but achieving them simultaneously with a high quality factor remains a major challenge. Therefore, the aim of this study is to present the theoretical foundations of 2D photonic crystal sensors and to focus on the design principles through which sensitivity and quality factor can be improved. Consequently, the study emphasizes the design and analysis of several structures of 2D photonic crystal sensors. The study is organized into several sections, where the first part focuses on reviewing the basic principles.

I.3.1. Photonic band gap

Photonic band gap refers to a range of wavelengths that are not allowed to propagate through a photonic crystal structure, resulting in high reflection and a corresponding trough in transmission. When this band gap is observed for all directions of propagation and for both polarization states of light, it is termed a complete photonic band gap [17].

The allowed wavelengths of light are called modes, and groups of these modes form photonic bands, whereas the forbidden regions are called forbidden bands, as illustrated in the band structure of a two-dimensional photonic crystal (Figure I.2)

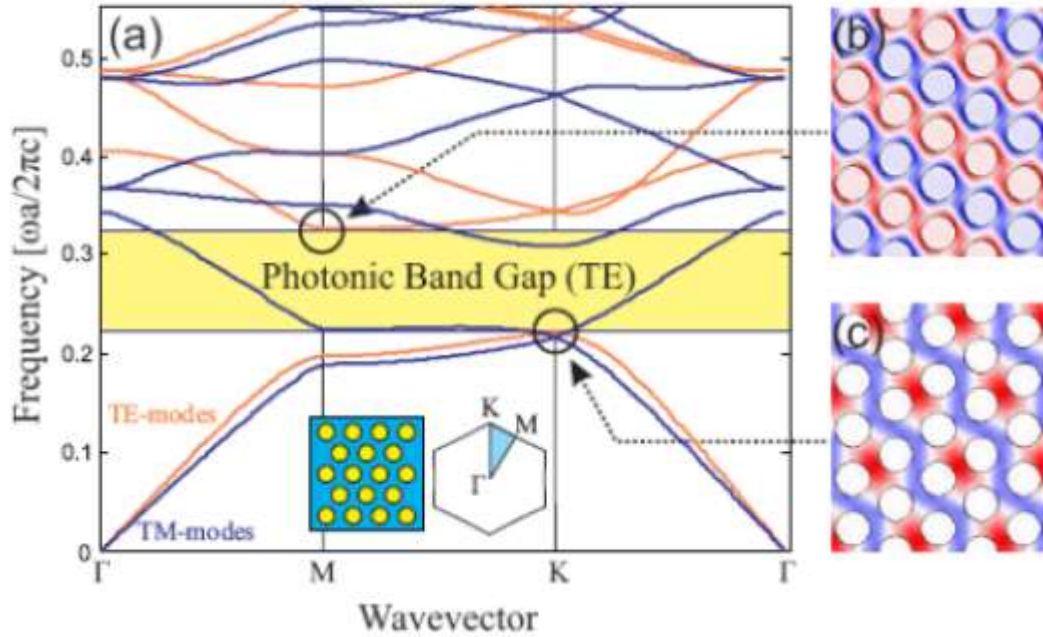


Figure I.2: Band structure in a two dimension photonic crystal lattice [18].

By introducing a defect into the periodic lattice, localized modes can appear inside the forbidden band, similar to impurity levels in semiconductor crystals. These defect modes exhibit strong electromagnetic field confinement, small mode volume, and low optical loss [19]. Light propagation in PhCs can be analyzed using Maxwell's equations and the theory of harmonic modes.

The photonic band gap is the most important feature of PhCs, as it prevents a certain range of frequencies from propagating [20]. By modifying the geometrical parameters or filling the air holes with appropriate materials, light propagation can be engineered on demand. This makes PhCs suitable for many devices such as filters [21], [22], switches [23], [24], and delay devices [25]. Among these, PhC based sensors are especially important due to their high sensitivity, compact size, and excellent integrability [26]. They are widely used in temperature [27], gas [29], [30], biochemical [31], humidity [32], and liquid sensing.

One of the most important PhC structures is the photonic crystal cavity (PhCC), formed by point defects in the periodic lattice. It provides strong spatial and temporal confinement of light, leading to a high quality factor Q and long photon lifetime [33]. The resonant wavelength of a PhC is extremely sensitive to variations in the surrounding medium, making it an excellent platform for high sensitivity optical sensing [34].

This classification arises from the similarity between the Schrödinger equation and the Helmholtz equation, where the refractive index in optics plays the same role as the electric potential in solid-state physics [35].

As known, the relationship between speed (c), frequency (ν), and wavelength (λ_0) is given by the following relationship:

$$\lambda_0 = \frac{c}{\nu} \quad (\text{I.1})$$

Given the relation (I.1), the wave vector (k) can be defined as follows:

$$K = \frac{2\pi}{\lambda_0} \quad (\text{I.2})$$

Then the relation between ω and wave vector k will be as follows:

$$\omega = cK \quad (I.3)$$

The relation (I.3) is called the emission field dispersion relation of vacuum. If the emission field is assumed to be in a homogeneous environment with a refractive index (η), the dispersion relation in the homogeneous environment will be obtained by Replacement of (I.4) and (I.5) relations in (I.1) and (I.3), respectively.

$$V = \frac{c}{\eta} \quad (I.4)$$

$$\lambda = \frac{\lambda_0}{\eta} \quad (I.5)$$

The density of states of emission field in V volume and in vacuum is given by:

$$D(\omega) = \frac{\omega^2}{\pi^2 c^3} \quad (I.6)$$

The density of states of emission field in a homogeneous environment can be obtained by replacing (I.4) relation in (I.6). The optical properties of atoms and molecules are dependent to $D(\omega)$, for example, by taking into account the spontaneous emission of a photon from the electron states of an atom or molecule, the spontaneous emission can be said to be proportional with $\omega D(\omega)$. If $D(\omega)$ is corrected, the optical properties of atoms and molecules will change. PhCs are one of the materials to correct $D(\omega)$. The following is shown how optical characteristics of PhCs can be changed to modify the optical properties.

I.3.2. Two dimensional photonic crystals (2D PhCs)

A two dimensional photonic crystal is structures that has a periodic adjustment of the dielectric permittivity in two directions of space, and is homogeneous with the third .These crystals are highly dependent on the polarization of the electromagnetic wave. Some ways to make these two dimensional structures:

a). The connected structure :

The elementary patterns have an index n_1 lower than the index n_2 . These structures are usually consisting of a periodic network of air holes drilled in a Silicon matrix see figure (I.3).

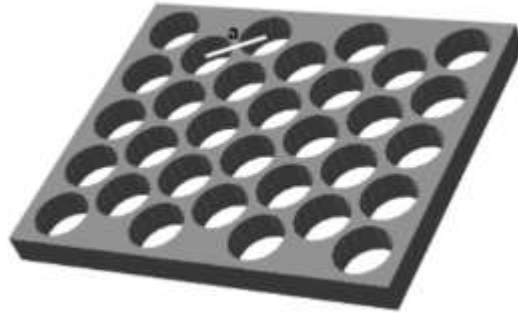


Figure I.3 : Connected 2D periodic structure.

b). The disconnected structure:

In this structure, the elementary patterns are of index n_1 greater than the index n_2 , it is consisting of dielectric or metal rods aligned periodically in the air or the foam. See figure (I.4) .

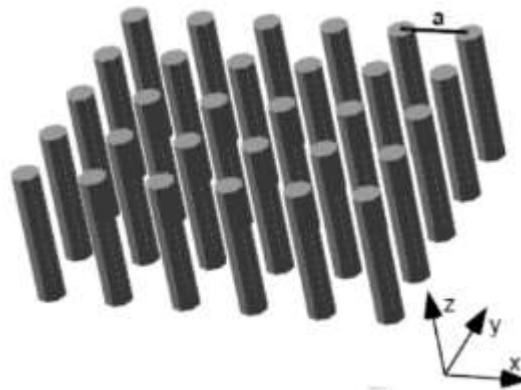


Figure I.4 : Disconnected 2D periodic structure.

c) The defects:

- Point defects:

Point defects in photonic crystals are created by either removing, adding, or modifying one or more crystals

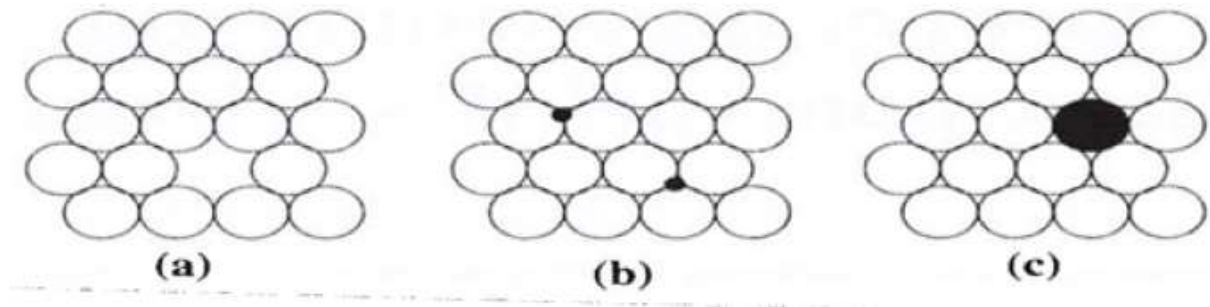


Figure I.5: Examples of simple one-time defects. (a) Deficiency. (b) Atom in interstitial position. (c) Atom in the substitution position.

- **Linear defects :**

A linear defect is introduced inside a light crystal if we reduce to a two-way periodicity in space. A 2D photonic crystal consists of insulating columns surrounded by air, or air holes drilled through an insulating Matrix. A waveguide can then be created by separating the two half levels in Figure (I.6).

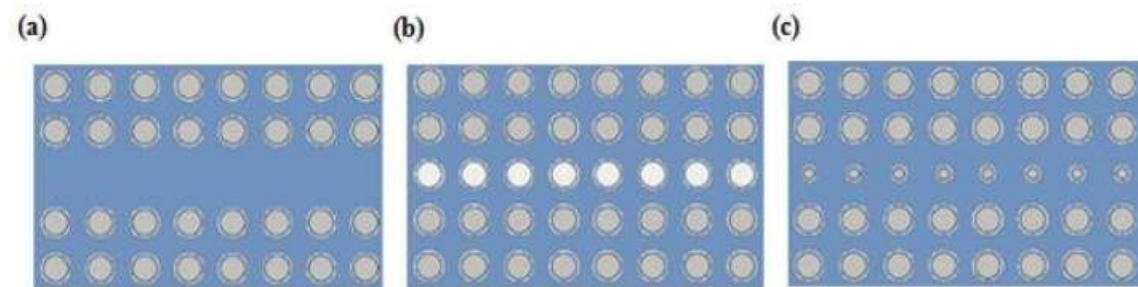


Figure I.6 : Examples of linear defects in a photonic crystal created (a) by omitting a single row of patterns, (b) by modifying the refractive index of a single row of patterns, (c) by varying the radius of a single row of patterns of the structure.

I.4. Principles of Optical Sensing

I.4.1. Refractive Index Sensing Mechanism

Refractive index (RI) sensors exploit the interaction of light with the surrounding medium to detect minute changes in the refractive index, enabling high-precision environmental sensing [36, 37]. RI based sensors represent the most diffused class of PhC sensors. In fact, a large number of advanced architectures (e.g., integrated micro-cavities and interferometry configurations) employ the refractive index sensing for detection. RI-based PhC sensors present numerous advantages such as minimal sample preparation without fluorescence labeling, real-time detection, high sensitivity and selectivity. In particular, the sensing principle consists in measuring RI changes of a bulk solution (e.g., deionized water, $n_{\text{Water}} = 1.33$ or air, $n_{\text{Air}} = 1$ ----- $\lambda = 1.55 \mu\text{m}$) due to the presence of chemical analytes or gases generally characterized by higher refractive indices. Applications in gaseous and aqueous environment have been studied to detect concentrations of chemical and biological species. In fact, by using these sensors, it is possible to quantify molecule and protein (e.g., streptavidin, DNA, mRNA) surface or volumetric density. Recently, advanced PhC-based sensors properly designed for single- molecule detection have been demonstrated to be able to detect the number of molecules concentrated into a complex solution [38]

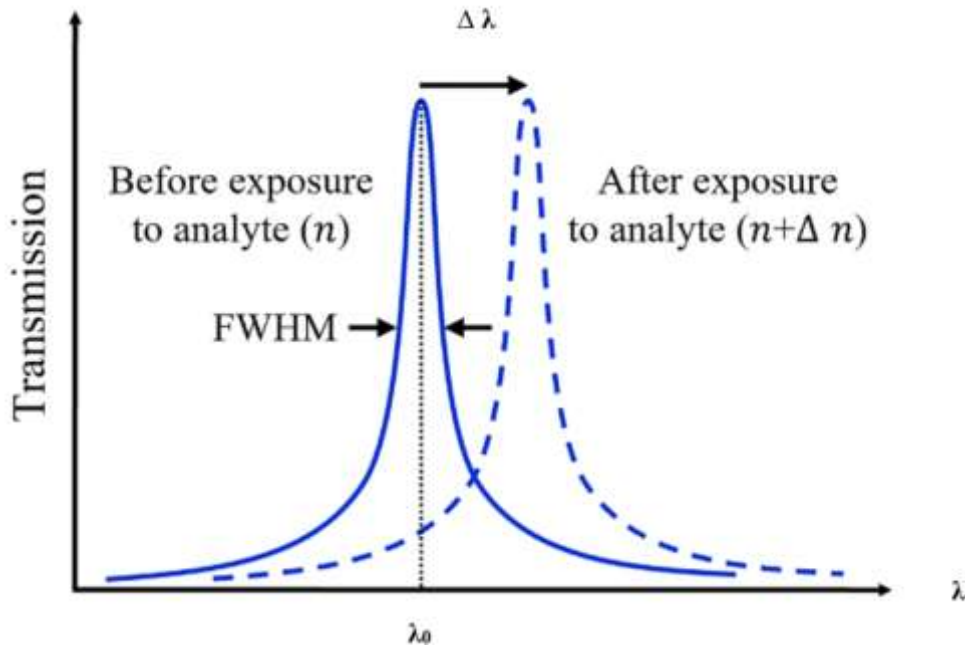


Figure I.7: The sensing performance of an optical RI sensor.

I.4.2. Wavelength Shift vs. RI variation

The optical refractive index (RI) sensor is used for detecting RI changes of the sample by measuring the resonant wavelength, angle and intensity [39]. Optical detection techniques can be broadly classified into two categories: fluorescence based detection and label-free detection, and label-free optical sensing do not rely on the use of expensive fluorophores and can perform quantitative estimation of targets in ultra-small sample volumes, which has gained a great deal of attention [40]. Up to now, a large number of optical RI sensors in different types of structure have been intensely investigated, such as surface plasmon resonant sensor [42], [43], fiber grating sensor [45], [46], and photonic crystal sensor [47], [48], [49]. Due to the photonic crystal sensor is an artificial optical sensing structure composed of dielectric materials, the characteristics of small absorption loss, high quality factor, and reusability compared with the former two, it has become a research hotspot of optical refractive index sensors.

I.4.3. Key Performance Metrics: Sensitivity, Q factor, Limit of Detection (LoD)

✓ Sensitivity:

The wavelength sensitivity S_λ represents a fundamental parameter for quantifying the sensor performance in case of wavelength interrogation scheme. S_λ is defined according to Eq. (I.7), as the ratio between the shift of resonant wavelength ($\Delta \lambda$) induced by the change of the background refractive index (Δn). Moreover, it is given in units of nm/RIU (refractive index unit), as [50]:

$$S_\lambda = \frac{\Delta \lambda}{\Delta n} \quad (I.7)$$

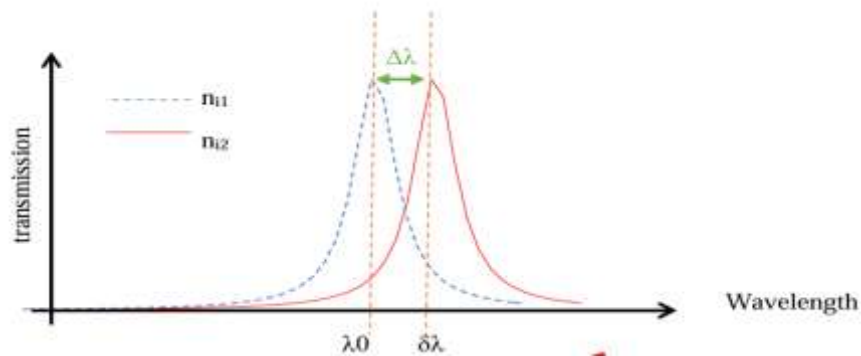


Figure I.8 : The transmission is function of wavelength with varying of refractive index

✓ **The quality factor:**

the quality factor Q and the wavelength sensitivity S_λ , have to be considered for appreciating PhC-cavity-based sensor performances. The Q -factor defines the shape of resonant peaks and consequently the value of the Full Width at Half Maximum (FWHM) and it is expressed as follows[38]:

$$Q = \frac{\lambda_{res}}{\Delta\lambda_{FWHM}} \quad (I.8)$$

Where as:

λ (resonant) represents the wavelength at which resonance occurs and $\Delta\lambda$ (FWHM) denotes the wavelength difference obtained at the Full Width at Half Maximum (FWHM) point.

✓ **Figure of merit (FOM) :**

The merit factor (FOM) is the next parameter, calculated as follows [40]:

$$FOM = \frac{Q \times S}{\lambda_0} \quad (I.9)$$

✓ **Limit of Detection (LoD):**

The Limit of Detection (LoD) of a photonic crystal (PhC) sensor represents the smallest change in refractive index (or the smallest analyte concentration) that can be reliably measured above the system noise. It is generally defined by the following relationship:

$$LoD = \frac{3\sigma}{S} \quad (I.10)$$

Où σ représente l'écart-type du bruit (fluctuations du signal) et S est la sensibilité du capteur (nm/RIU).

I.5. Simulation Framework

Recently various methods have been proposed to calculate the band structures of PhCSs, such as the plane-wave expansion method (PWEM), the transfer matrix method the finite-difference time-domain (FDTD) method and the finite-element method. Among these methods, the PWEM is the more popular technique. The PWEM is used for calculation of the band structure of general periodic structures in which the structures extend periodically in all dimensions. However, the PhCS has only two-dimensional periodicity. To employ the three-dimensional PWEM, we can impose a third-dimensional periodicity by introducing a periodic sequence of slabs separated by a sufficient amount of background region to ensure electromagnetic isolation.[51]

This is called the supercell technique.[52] The guided modes are then localized within the PCS so that the additional periodicity of the slabs with large separation will not affect the modes' eigen frequencies. However, because of the existence of the light cone that represents a boundary between radiation modes and truly guided modes, the eigen modes may be cast into two categories. One is the leaky mode, which is extended infinitely in the cladding region outside the slab, and the other is the truly guided mode, which is the state localized in the slab. States that lie below the light line in the band diagram cannot couple with modes in the bulk background, so these discrete bands are confined. By introducing the artificial periodicity in the z direction, the guided modes below the light cone can be determined by conventional PWEM with the supercell technique. However, for the leaky modes that lie above the light cone, this method is no longer appropriate.

I.5.1. Plan Wave Expansion (PWE)

The Plane Wave Expansion Method is a computational technique used to solve for the optical behavior (photonic band structure) of a photonic crystal by expressing the electromagnetic fields as a sum of plane waves and solving an eigenvalue problem derived from Maxwell's equations. It is particularly convenient for periodic structures such as PhCs since it is based on the expansion of periodic electromagnetic fields and permittivity functions into Fourier series, whose components are then treated by linear-algebraic numerical techniques. The same procedures have been carried out earlier in the frame of coupled-wave theory (or Fourier modal theory) of light diffraction by gratings (which can be referred to as PhC slabs). It has been reported that the numerical effectiveness of the PWE method, represented by the convergence rate in the truncated basis of the Fourier components, strongly depends on the specific implementation of the method, since there are various possibilities of the expansion of the material and field parameters [53, 54]. In particular, periodic

discontinuities typical for PhC's elements cause rather poor convergence and extremely time- and memory-consuming computer simulations, especially when the electric field vector has the nonzero perpendicular component to the permittivity discontinuities.

I.5.2 . 2D Finite.Difference Time.Domain (FDTD)

Finite Difference Time Domain (FDTD) methods. During the 1970s and 1980s, a number of researchers realized the limitations of frequency domain integral equation solutions of Maxwell's equations. This led to early explorations of a novel alternative approach: direct Time. Domain solutions of Maxwell's differential (curl) equations on spatial grids or lattices. FDTD and related space grid time domain techniques are direct solution methods for Maxwell's curl equations.[41]

- Electromagnetic theory governed by Maxwell's equations. In a source free, non-magnetic medium, the behavior of the electric field $\mathbf{E}$ is described by the vector wave equation:

$$\nabla^2 \mathbf{E}(\mathbf{r}) + \frac{\omega^2}{c^2} \epsilon(\mathbf{r}) \mathbf{E}(\mathbf{r}) = 0 \quad (\text{I.11})$$

$$\nabla \times \vec{E}(\vec{r}, t) = -\frac{\partial \vec{B}(\vec{r}, t)}{\partial t} \quad (\text{I.12})$$

$$\nabla \times \vec{H}(\vec{r}, t) = \vec{j}(\vec{r}, t) + \frac{\partial \vec{D}(\vec{r}, t)}{\partial t} \quad (\text{I.13})$$

$$\vec{\nabla} \cdot \vec{D}(\vec{r}, t) = \rho(\vec{r}, t) \quad (\text{I.14})$$

$$\vec{\nabla} \cdot \vec{B}(\vec{r}, t) = 0 \quad (\text{I.15})$$

Where :

- $\epsilon(\mathbf{r})$ = represents the spatially periodic dielectric function of the photonic crystal .
- ω = is the angular frequency.
- c = is the speed of light in vacuum .

The introduction of a defect within the periodic lattice leads to the formation of localized resonant modes inside the photonic band gap. These modes are highly sensitive to variations in the refractive index of the surrounding medium. A change in refractive index Δn results in a measurable shift in the resonant wavelength $\Delta\lambda$, which forms the basis of the sensing mechanism.

I.5.3. Polarization of the electromagnetic wave (TE and TM)

The polarization of the light affects the 2D PhCs dispersion equations. The electromagnetic field in this instance has been described by two separate polarizations, the Transverse Electric (TE) polarization and the Transverse Magnetic (TM) polarization see figure (I.9) The H field in TE polarization has a single component normal to the plane, and the E field is orientated in the periodicity plane. The electromagnetic field has three components: E_x , E_y , and H_z , with zero for the other components. The field in TM polarization has the form (H_x, H_y, E_z) , with the functions of E and H reversed. With (r) representing the hole radius and (a) representing the lattice period, we consider a triangular lattice of air holes in a dielectric matrix with $\epsilon = 12$. Therefore, electromagnetic waves in 2D crystals can be classified into two polarizations, TE and TM, and propagate in the plane perpendicular to the rods. To create a total band gap, the band gaps that arise in each scenario must overlap [27].

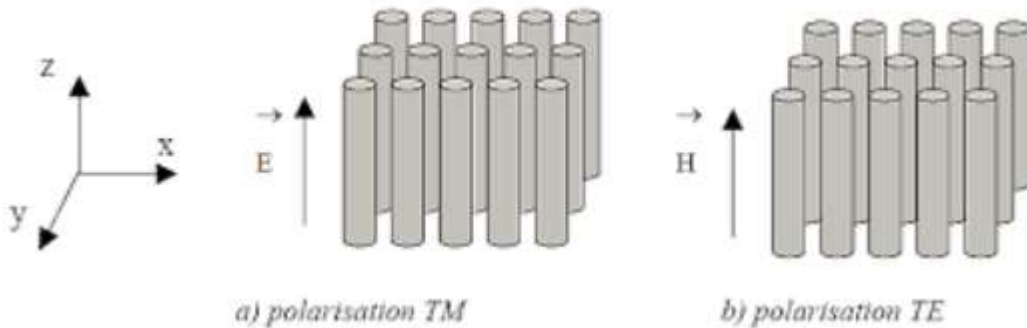


Figure I.9: Transverse magnetic TM and transverse electric TE polarization.

I.5.4. Photonic bandgap analysis using RSOF T Simulator

Hexagonal lattice of 2D photonic crystals consisting of 15×15 circular holes in silicon slab along the X and Z axes respectively presented in this example. The structure will be elaborated using holes air with refractive index of $n_{\text{air}}=1$ RIU placed in the in silicon slab (Si) background with a refractive index of $n_{\text{Si}}=3.42$ RIU, with a period of $a = 0.47 \mu\text{m}$ and a radius of the air holes is $r = 0.14 \mu\text{m}$. The geometric diagram of the structure based on 2D photonic crystals is presented in the figure (I.10).

In this case, we used our own calculated results and numerical parameters to obtain the hexagonal structure diagram illustrated in the previous example.

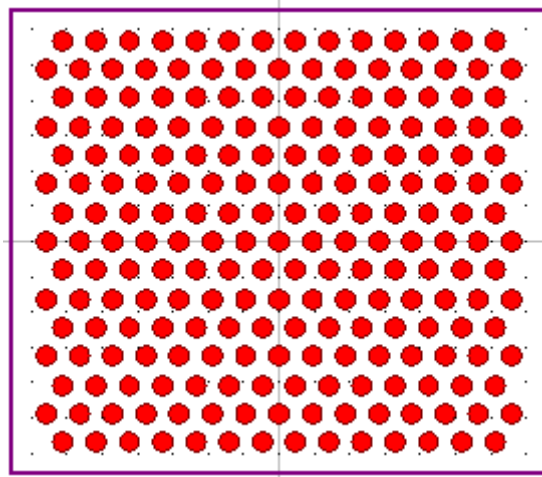


Figure I.10: The diagram of the hexagonal structure used for the biosensor design is based on 2D-Photonic crystal.

Figure I.11, Shows the TE/TM photonic band structure of a hexagonal photonic crystal calculated using the plane wave expansion (PWE) method (using the BandSolve module of RSOF T simulator). Two photonic band gaps are observed for TM polarization. The first band is located between the frequencies 0.20953 and 0.27635 and its wavelength ranges between $2.243115 \mu\text{m}$ and $1.700741 \mu\text{m}$, the second band is located between the frequencies 0.59102 and 0.62019 and its wavelength ranges between $0.75783 \mu\text{m}$ and $0.79523 \mu\text{m}$. these band gaps correspond to frequency regions where electromagnetic wave propagation inside the photonic crystal is forbidden.

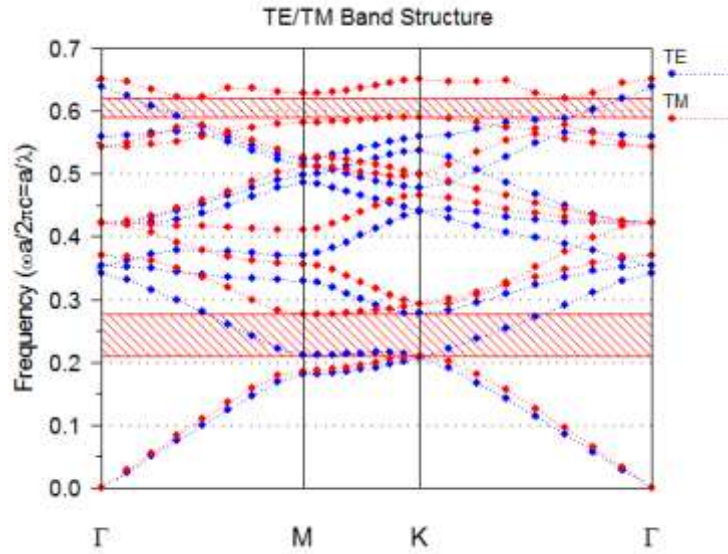


Figure I.10 : Presents a diagram of photonic bandgaps of the PhC hexagonal structure

This band structure was obtained through numerical simulation using the plane wave expansion (PWE) method for the designed hexagonal photonic crystal.

I.6. Conclusion

Photonic crystals are one of the leading scientific innovations that have made a quantum leap in many technical and scientific fields. Thanks to their unique structure that enables them to accurately control the passage of electromagnetic waves, photonic crystals have become key tools in the development of advanced technologies, starting with optical communications. In this chapter, we provided basic information about photonic crystals, where we defined them and mentioned their natural and artificial types and the principles of each, and then we touched on the characteristics of photonic crystals and various types of defects, mentioning the possibility of controlling photonic crystals in the propagation of light based on the band gap property (BGP).

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Chapter II:

State of the Art and Photonic Crystal Sensor Architectures

II.1.Introduction

In this chapter, we will provide a comprehensive overview of photonic crystal (PhC)-based optical sensors, which have emerged as a powerful platform for label-free biosensing due to their ability to confine light at the nanoscale and enhance light–matter interactions. The discussion will begin with the fundamental principles of PhC sensors, followed by a critical review of the historical development and state-of-the-art sensitivity limits, expressed in terms of nm/RIU and limit of detection (LoD). Key architectural configurations will then be examined, including PhC slabs, nanocavities, and slot-waveguide designs. Finally, based on an analysis of existing literature, the chapter will identify specific research gaps and clearly articulate the original contributions of the present work.

II.2. Photonic Crystal Sensors

PhC biosensors represent one of the most advanced optical sensing technologies used for biological detection. A biosensor generally consists of two main components: a biological recognition element and a transducer. The biological element may include enzymes, antibodies, antigens, or DNA fragments that are capable of specifically recognizing the target analyte. The transducer, which can be optical, electrochemical, or mechanical, converts the biological interaction into a measurable signal.

In PhC biosensors, the sensing mechanism is mainly based on the interaction between light and the periodic dielectric structure of the photonic crystal. When the analyte interacts with the sensing region, it causes a change in the local refractive index, which leads to a shift in the resonance wavelength or transmission spectrum. This optical variation can then be measured and used to determine the presence or concentration of the target biomolecule.

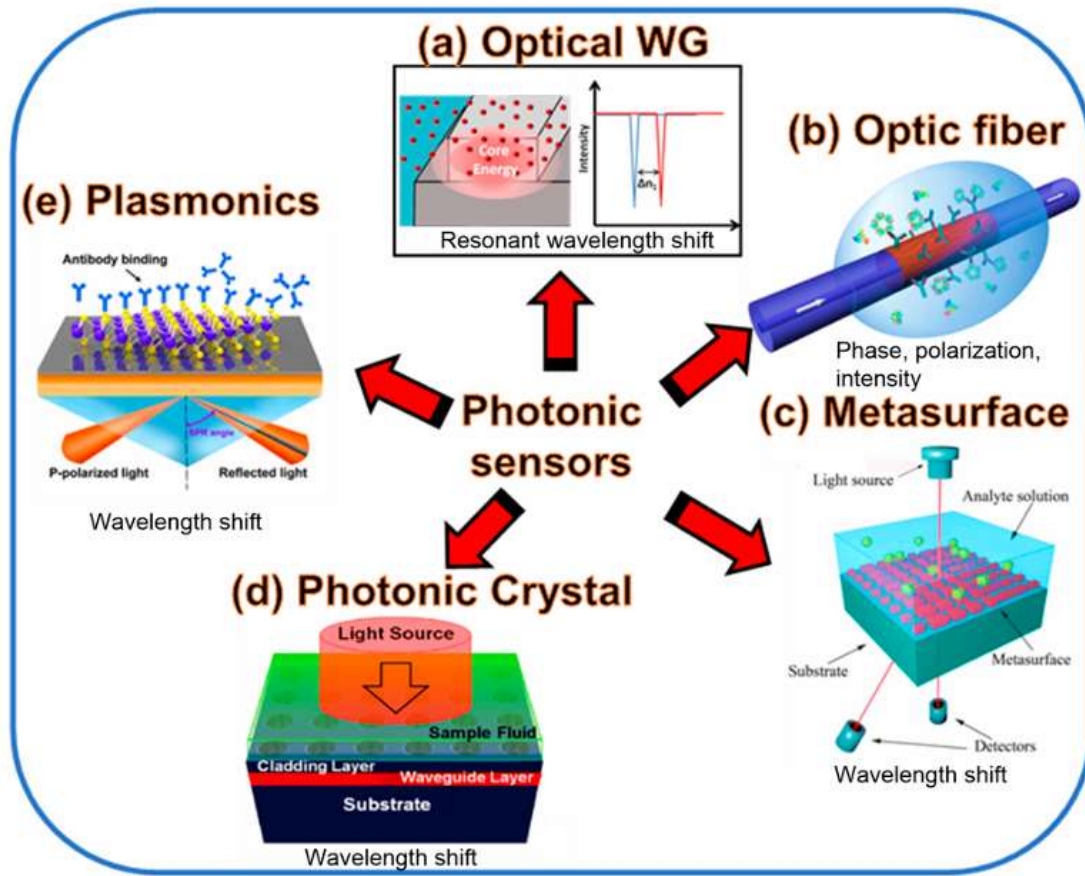


Figure II.1 : The photonic sensing technologies based on (a) optical WG, (b) Optical Fiber (c) Meta surface , (d) Photonic Crystal , and (e) plasmonics.[1]

II.3. State of the Art in Photonic Crystal Biosensors

This part provides a thorough review of the existing literature on two-dimensional photonic crystal (2D PhC) biosensors, with a critical focus on sensitivity enhancement strategies, fabrication approaches, and their applicability to clinical diagnostics. It also highlights key gaps in current research that serve as the motivation for the present study.

II.3.1. Historical Development of Photonic Crystal Sensors

The field of photonic crystal-based sensing emerged following the seminal work of Yablonovitch (1987) and John (1987) on photonic band gap materials. This discovery opened new possibilities for manipulating light in optical devices and photonic structures. With the development of nanofabrication technologies in the 1990s, scientists were able to fabricate photonic crystal structures and photonic crystal fibers containing periodic arrays of air holes, which significantly improved light confinement and light–matter interaction. These unique optical properties led to the development of photonic crystal sensors with high sensitivity for detecting small variations in refractive index, making them promising platforms for biological and chemical sensing applications [2],[3].

The transition from fundamental physics to practical biosensing applications began in the early 2000s, with pioneering demonstrations by:

- **Cunningham et al. (2002):** First demonstration of photonic crystal surfaces for high-throughput screening. [4]
- **Lončar et al. (2003):** Initial work on photonic crystal nanocavities for refractive index sensing.[5]
- **Fan and White (2008):** Theoretical establishment of the relationship between Q-factor and sensitivity. [6]

Advances in nanofabrication and surface chemistry have driven the evolution from bulk refractive index sensors to functionalized biomolecular detectors.

II.3.2. Critical Review of Reported Sensitivity Limits (nm/RIU and LoD) :

Photonic crystal biosensors have attracted considerable attention due to their ability to detect very small variations in the refractive index of biological and chemical samples. The performance of these sensors is commonly evaluated using two important parameters: sensitivity and limit of detection (LoD). Sensitivity is usually expressed in nm/RIU and represents the shift in resonance wavelength caused by a change in the refractive index of the analyte. Several studies have reported sensitivities ranging from approximately 100 nm/RIU to more than 1000 nm/RIU depending on the sensor architecture, such as photonic crystal

waveguides, nanocavities, and slot structures. In addition, the limit of detection describes the minimum refractive index variation that can be accurately measured by the sensor. Recent research has demonstrated LoD values reaching 10^{-6} RIU and even lower in optimized photonic crystal structures. Despite these advances, improving sensitivity while maintaining a high quality factor and fabrication feasibility remains a significant challenge in the development of photonic crystal biosensors [7],[8].

Ref	Author / Year	Structure Type	Sensitivity (nm/RIU)	LoD (RIU)	Remarks
[7]	Lee et al., 2007	2D PhC slab (waveguide)	~100 – 200	$\sim 10^{-4}$	silicon-based biosensor
[8]	Mandal et al., 2008	PhC microcavity	~300 – 500	$\sim 10^{-5}$	High Q-factor cavity
[9]	Skivesen et al., 2007	PhC waveguide	~200 – 400	$\sim 10^{-5}$	Label-free biosensing
[10]	Dorfner et al., 2008	PhC nanocavity	~500 – 800	$\sim 10^{-6}$	Enhanced light confinement
[11]	Di Falco et al., 2009	Slot PhC waveguide	~800 – 1200	$\sim 10^{-6}$	Strong field localization in slot
[12]	Recent works (2020–2024)	Optimized PhC sensors	>1000	$\leq 10^{-6}$	Advanced nanofabrication

Table II.2 : Summary of reported photonic crystal biosensor performances .

From Table II.2 it can be observed that the sensitivity of photonic crystal biosensors has significantly improved over time, especially with the use of nanocavities and slot waveguide structures. However, achieving both high sensitivity and low limit of detection while maintaining fabrication simplicity remains a major challenge.

II.4. 2D Photonic Crystal sensor Architectures

Photonic crystal sensors can be implemented using different structural architectures that enhance light–matter interaction and improve sensing performance. Among the most commonly used architectures are photonic crystal slabs, photonic crystal nanocavities, and slot photonic crystal waveguides. These configurations enable strong confinement of electromagnetic fields and enhance sensitivity to refractive index variations, making them suitable for biochemical sensing applications.

II.3.1. Sensor based on photonic crystal slabs and membranes

Photonic crystal slabs are formed by a thin dielectric membrane patterned with a periodic array of air holes. This periodic arrangement generates a photonic bandgap that governs light propagation within the plane of slab. Meanwhile, vertical confinement is ensured by total internal reflection. Such a configuration enables strong interaction between the optical field and the surrounding medium, making it particularly well-suited for refractive index sensing applications.

In this next part we will present some structure based on Photonic Crystal slabs.

Sabrina Jahns and others a handheld photonic crystal biosensor for label-free and multiplexed detection of several biomarkers using a spectrometer-free imaging system. The photonic crystal slab is fabricated on a glass substrate by replicating a periodic grating master stamp with a period of 370 nm into a photoresist via nano-imprint lithography and deposition of a 70-nm titanium dioxide layer. Experimental results demonstrate the detection of CD40, EGF, and streptavidin, as well as thrombin detection using aptamers.[13]

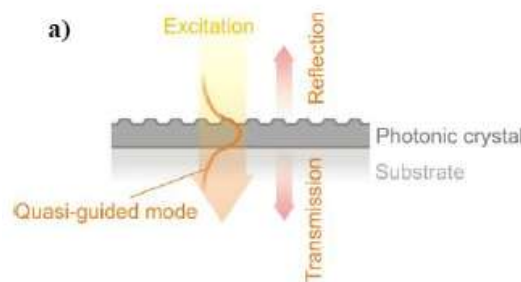


Figure II.2: Schematic of photonic crystal slab (PCS). [13]

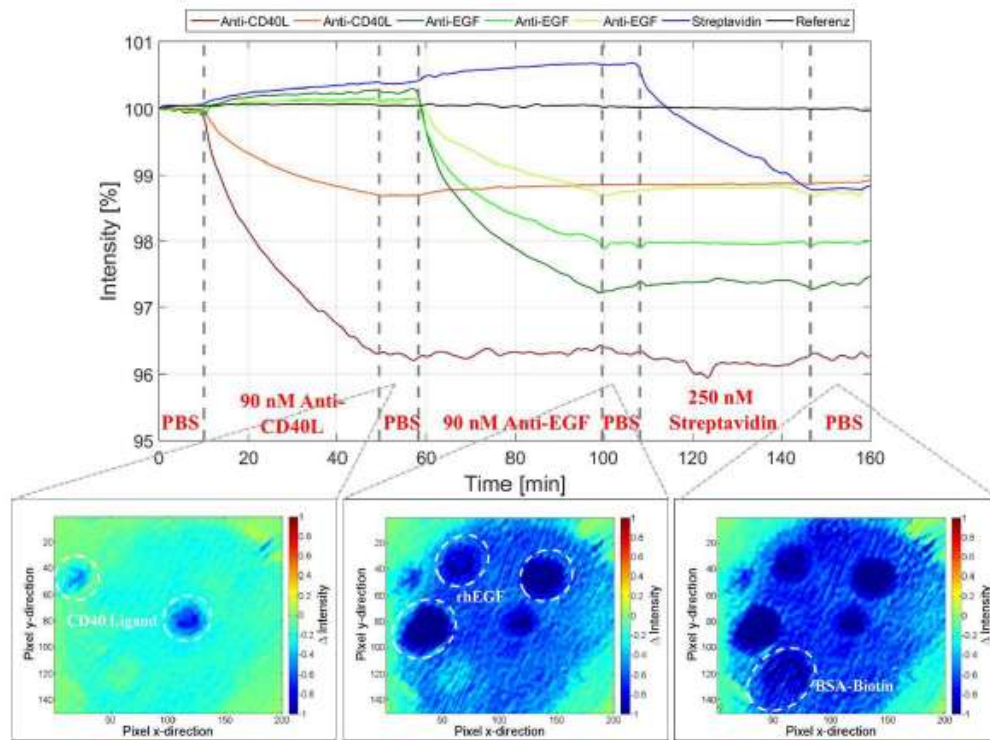


Figure II.3 : The association of first 90.0 nM CD40 ligand antibodies (150 kDa), second 90.0 nM EGF antibodies (150 kDa) and third 500 nM streptavidin (60 kDa) all dissolved in DPBS is observed in the normalized intensities of the transmitted light, while no unspecific binding events are visible in the signal sequence. .[13]

In 2013, Costa Nicolaou and colleagues enhanced the detection limit of 2D photonic crystal slab refractive index sensors using dark mode perturbation. They demonstrated a 300 nm thick, $300\ \mu\text{m} \times 300\ \mu\text{m}$ 2D dielectric photonic crystal slab membrane with a high quality factor of 10,600. The design uses alternating nano-hole sizes to couple light into perturbed dark modes, reducing fabrication accuracy requirements.

A new layer architecture enhances the electric field at the sensing interface, achieving a spectral sensitivity of $>800\ \text{nm}/\text{RIU}$. This value corresponds to more than 0.8 of the theoretical upper limit of sensitivity. .[14]

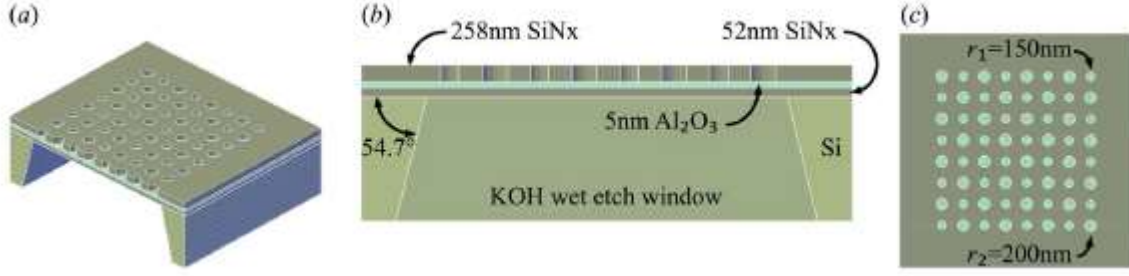


Figure II.4: (Color online) Schematics of the liquid/SiNx/air suspended membrane design.

(a) 3D view of the layers structure and window after KOH wet etch removal of the Si substrate, (b) layer structure cross-section and, (c) top view demonstrating the fabricated CPCS nano-hole array. .[14]

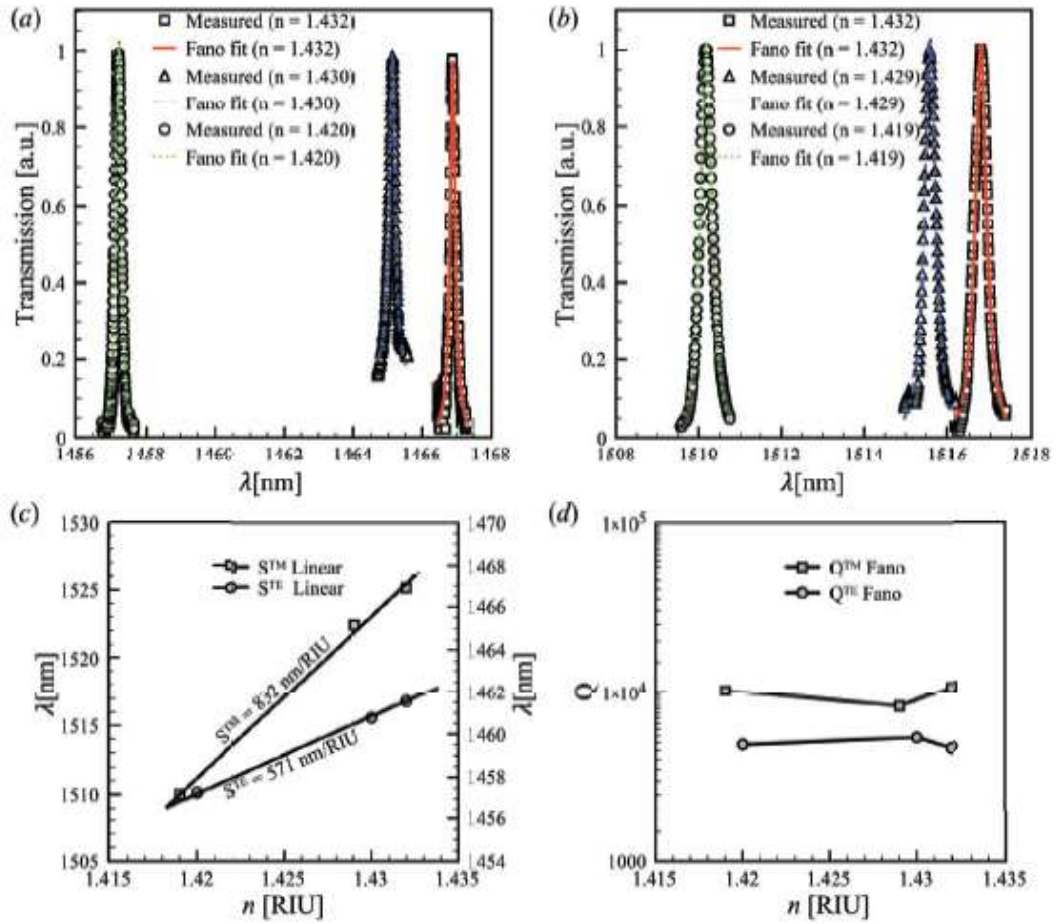


Figure II.5: (Color online) Sensitivity evaluation of CPCS TM and TE like GR modes with same parameters (a) Measured TM-like experimental spectral waveforms for 3 different RI's (b) TE-like experimental spectral waveforms for 3 different RI's (c) Fitted experimental TM- and TE-like sensitivity values and, (d) experimental TM- and TE-like quality factors. .[14]

II.3.2. Sensor based on photonic crystal Nanocavities

By introducing a defect in the periodic lattice, localized resonant modes with ultra-high Q-factors can be achieved. Key configurations include:

- **L3 cavities:** Three missing holes in a line defect, offering moderate Q-factors (10^4 – 10^5) with high field concentration.
- **H0 and H1 cavities:** Single-point defects providing the smallest mode volumes.
- **Heterostructure cavities:** Engineered to achieve Q-factors exceeding 10^6 in silicon.

These structures achieve exceptional sensitivity due to strong light-matter interaction within the modal volume, but fabrication precision requirements are stringent (sub-5 nm alignment tolerance).

Photonic crystal nanocavity sensors exploit the unique optical properties of defect sites within a periodic dielectric structure. By introducing a deliberate defect into the photonic crystal lattice, a nanocavity is formed that tightly confines light within a minute volume for extended periods, resulting in an ultra-high quality factor (Q). This intense light-matter interaction makes the cavity's resonant wavelength exquisitely sensitive to local refractive index changes caused by target analyte binding. When molecules attach to the functionalized cavity surface, the resonance shifts in proportion to the analyte concentration, enabling label-free, real-time detection with exceptional sensitivity—down to single-molecule levels in some cases. These compact, chip-integratable sensors are highly promising for medical diagnostics, environmental monitoring, and chemical sensing.

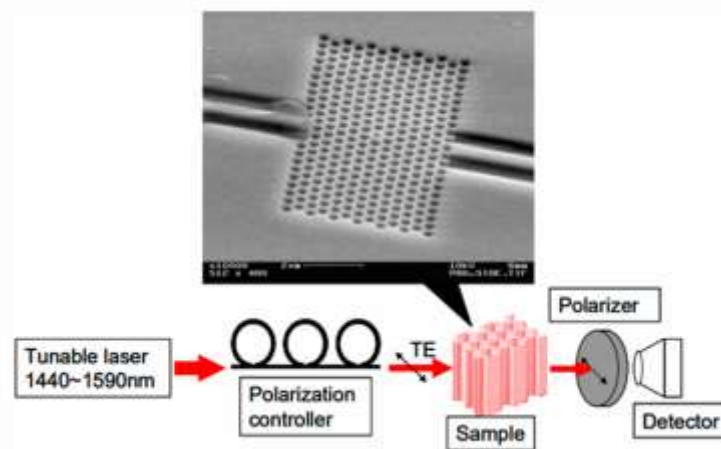


Figure II.6 : Photonic crystal nanocavity sensor [1]

The fundamental sensing principle relies on shifts in the cavity's resonant wavelength. When a target analyte (e.g., a gas, liquid, or biomolecule) enters the cavity's active region, it changes the local refractive index. This alteration causes a detectable shift in the transmission spectrum, and the magnitude of this shift reveals the analyte's concentration or presence.

As an example, one study designed a portable and simple two-dimensional photonic crystal microcavity sensor for detecting gases such as ammonia, methane, carbon monoxide, acetylene, ethylene, and ethane. The sensor's performance is continuously optimized by adding point defects, introducing a ring cavity, and varying the radius of the dielectric rods in the microcavity. [15]

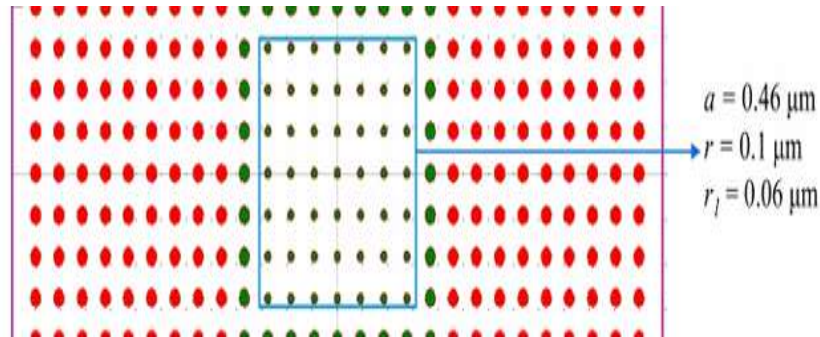


Figure II.7 : Structural design diagram of the 2-D PhC microcavity gas sensor. [15]

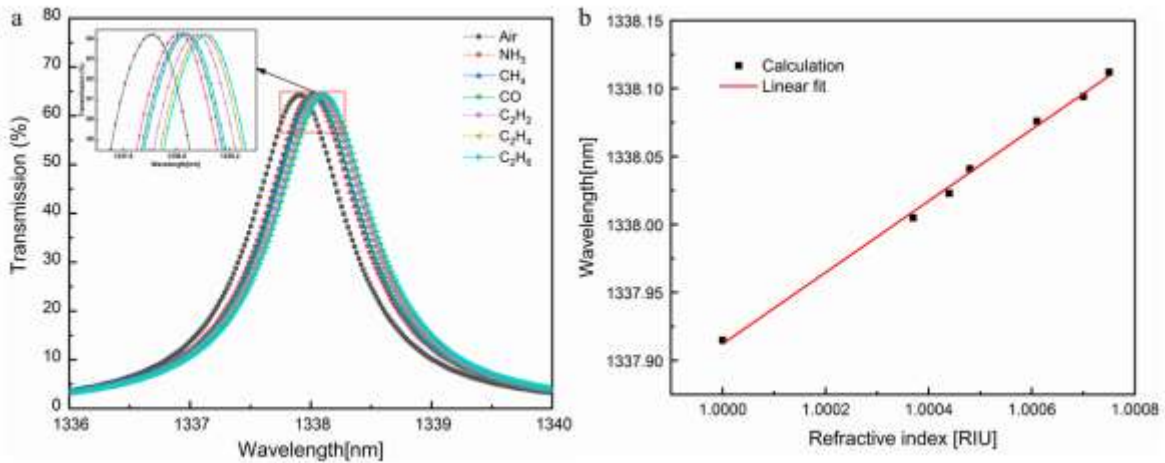


Figure II.8 : (a) Transmission spectra obtained at the waveguide output of the 2-D PhC microcavity sensor (b) wavelength values at the resonant peaks of the transmission spectra for seven gases (including air) and the linear fitting curve corresponding to the refractive index of the gases. [15]

II.3.3. Sensors based on photonic crystal waveguides

Photonic crystal waveguide-based sensors represent a significant advancement in optical sensing technology, harnessing the unique light-manipulating properties of photonic crystals (PhCs) to achieve exceptional sensitivity and miniaturization. These sensors operate on a fundamental principle: any physical or chemical change that alters the periodicity or refractive index of the PhC structure will induce a measurable change in the properties of light (intensity, phase, or spectral characteristics) passing through or reflected from the device.[1]

The field is rapidly evolving, with two primary technological pathways emerging: Photonic Crystal Fibers (PCFs) and integrated Photonic Crystal Waveguides (PhCWs). While both leverage photonic crystal principles, their architectures and applications differ significantly, as summarized in the table below.

Both PCF and PhCW sensors exploit the photonic bandgap effect, creating "defects" that act as waveguides or resonant cavities. The key to their function is enhancing the interaction between light and the **analyte**—the substance being measured.

- **Waveguide-Based Sensing in PhCs:** In an integrated PhCW, light is confined to a line-defect waveguide. By creating a nanocavity next to this waveguide, a very sharp resonance (anti-peak) is created in the transmission spectrum [16]. When an analyte binds to the surface of the cavity, it changes the local refractive index, shifting the resonance wavelength. This shift is the sensor's signal. The sensitivity of such devices can be remarkably high. For example, recent research on a dual-cavity 2D PhC sensor achieved a **sensitivity of 9261.54 nm per Refractive Index Unit (nm/RIU)**, with a figure of merit exceeding 4.5×10^7 , making it exceptionally effective for precise biomedical applications like cancer cell detection

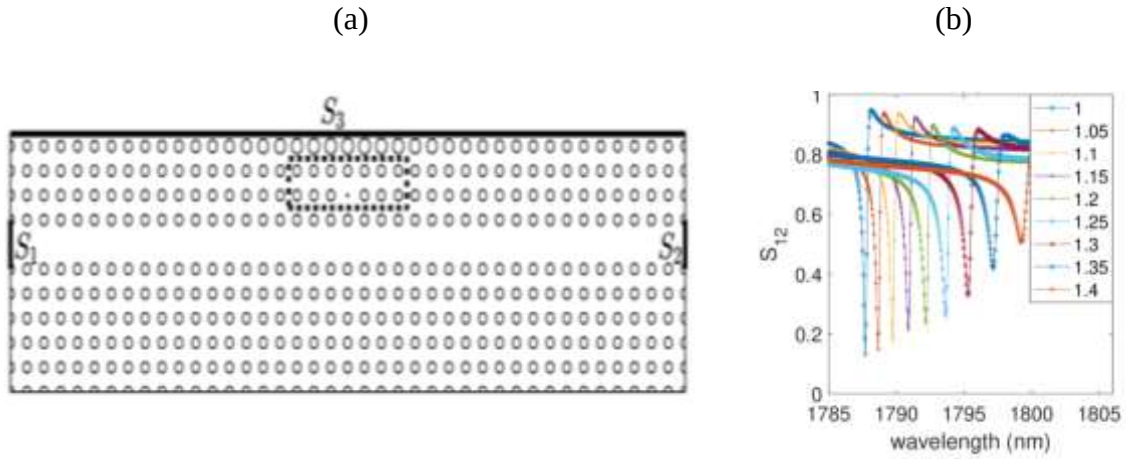


Figure II.9 : (a) Structure of the integrated photonic crystal waveguide and edge-cavity, which are coupled by a micro-cavity within the dashed-rectangular between them. (b) Transmittance to the S2 port versus wavelength around the resonant peak at 1787.7 nm for varying value of air refractive index n_s [16].

Slow-Light Enhancement: In PhCWs, engineers can design the structure to dramatically reduce the group velocity of light—a phenomenon known as the "slow-light effect." Slowing light down effectively increases its interaction time with the analyte, leading to a significant boost in sensitivity, especially in absorption-based sensing.

As an example, one study experimentally investigated the slow-light characteristics and gas-sensing performance of 1D and 2D photonic crystal waveguides (PCWs) in the near-IR (NIR) region. The proposed 2D PCW exhibited a high group index of up to 114, albeit with high propagation loss. The limit of detection (LoD) for acetylene (C_2H_2) was 277 parts per million (ppm) for a 1 mm waveguide length and an averaging time of 0.4 s. [17]

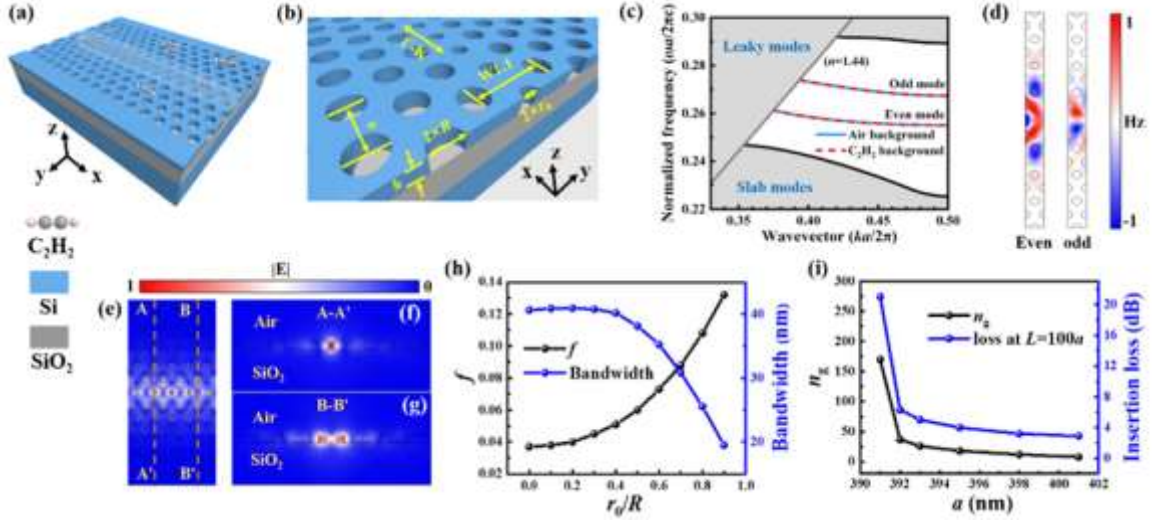


Figure II.10 : (a) 3D schematic of the 2D PCW with a 220 nm thick Si layer and a 2 μ m thick BOX layer. (b) Geometric parameters of the 2D PCW including the lattice constant a , radius of bigger air holes R , radius of center defect holes r_0 , waveguide width $W_{1.1}$, thickness of Si h , and direction of the defect $\Gamma - K$. (c) Dispersion diagram under air and pure C₂H₂ background. (d) H_z distributions of even mode and odd mode (e) $|E|$ distribution of the even mode (f) at the cross section through a defect hole and (g) through Si slab in (e). (h) Guided mode bandwidth below the SiO₂ light line in terms of wavelength (nm). (i) Simulated curves of group index and insertion loss versus the lattice constant. [17]

II.5. Identified Research Gaps and Contribution of This Work

In particular, photonic crystal biosensors have attracted considerable attention due to their high sensitivity to refractive index variations and their ability to detect small changes in biological samples. However, several challenges remain in improving the performance of these sensors for biomedical applications such as skin disease detection. Most previous studies focused on general biosensing applications without specifically targeting biomarkers associated with skin disorders such as vitiligo. Furthermore, optimizing photonic crystal structures to enhance light-matter interaction with biological analytes is still an active area of research.

In this work, a two-dimensional photonic crystal biosensor is proposed for the detection of biological variations related to vitiligo. The designed structure aims to enhance the interaction between the electromagnetic field and the sensing medium in order to detect variations in refractive index associated with melanin concentration. Through structural optimization and

numerical simulation, this work contributes to the development of a highly sensitive photonic crystal biosensor that may support future biomedical diagnostic applications .

II.6. Conclusion

In conclusion, this chapter has systematically reviewed the operating principles, historical evolution, and performance benchmarks of photonic crystal biosensors. The critical analysis of reported sensitivity limits revealed that while PhC nanocavities and slot-waveguides offer exceptional refractive index sensitivity and low LoD. The identified research gaps directly motivate the contributions presented in this work. Collectively, this review establishes the foundation for the novel PhC sensor designs developed and validated in subsequent chapters.

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Chapter III

Design and Numerical Modeling of the Two- Dimensional Photonic Crystal Biosensor

III.1 Introduction

This chapter presents the design and numerical modeling of the proposed two-dimensional photonic crystal (2D PhC) biosensor, developed for clinical diagnostics with a specific focus on early vitiligo detection. This chapter aims to establish the structural configuration and simulation framework necessary to investigate and enhance the sensitivity of the proposed sensing platform.

The chapter begins with the structural design of the photonic crystal, in which the periodic lattice configuration, material properties, and key geometrical parameters, such as the lattice constant, air-hole radius, and slab thickness, are defined. Particular emphasis is placed on the integration of a ring-cavity defect within the photonic crystal lattice, which acts as the sensing region of the device [1]. This ring-cavity structure enables strong light confinement and increases the interaction between the optical field and the infiltrated analyte, which is essential for achieving high sensing performance [2].

The chapter further describes the numerical simulation methods and computational tools used to analyze the optical properties of the proposed biosensor. Numerical techniques such as the Plane Wave Expansion (PWE) method are employed to determine the photonic band structure and identify the photonic band gap, while the Finite-Difference Time-Domain (FDTD) method is used to analyze the resonance behavior and electromagnetic field distribution within the ring cavity structure [3,4]. In addition, the design strategy focuses on enhancing the sensitivity of the biosensor through careful optimization of the ring cavity geometry and the photonic crystal parameters. The sensing mechanism is based on monitoring the shift in the resonance wavelength caused by variations in the refractive index of the infiltrated biological sample. These refractive index changes are associated with analytes related to early vitiligo conditions, allowing the proposed biosensor to potentially contribute to non-invasive and early-stage clinical diagnosis.

Overall, this final chapter establishes the design principles, structural configuration, and simulation setup of the proposed ring-cavity photonic crystal biosensor.

III.2 Design of the Two-Dimensional Photonic Crystal Structure

The proposed PhC structure consists of a (23×23) periodic lattice, as illustrated in Figure III.1(a). The defect-free photonic crystal exhibits a wide photonic bandgap for TM-polarized

light within the wavelength range of 1130–1860 nm, as shown in Figure III.1(b). To operate at the telecommunication wavelength of 1.55 μm , the photonic crystal lattice was designed with a lattice constant of 0.47 μm and an air-hole radius of 0.19 μm . These parameters allow the structure to support strong optical confinement and provide a suitable platform for high-sensitivity biosensing.

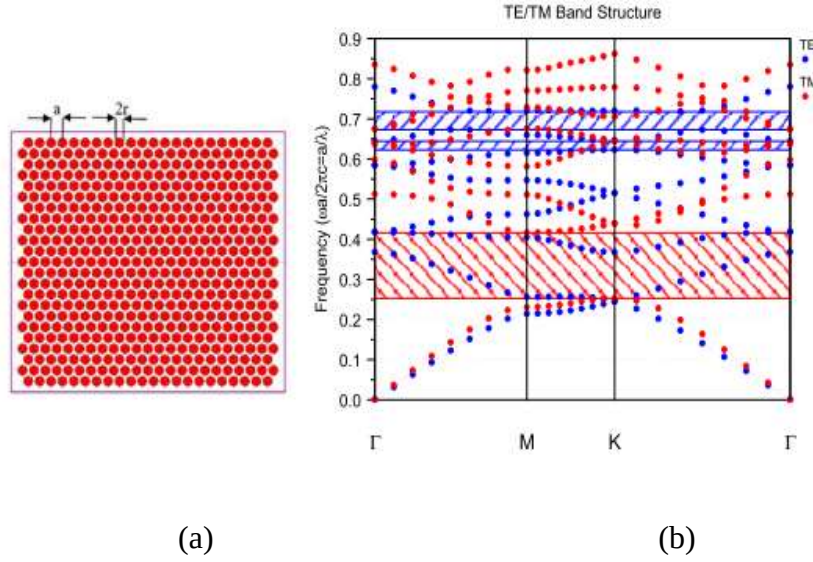


Figure III.1. (a) Layout of the proposed two-dimensional photonic crystal (2D-PhC) structure, (b) Photonic band diagram of the designed 2D-PhC structure.

III.3 Design Parameter Optimization

The performance of the proposed photonic crystal biosensor is strongly influenced by its structural parameters. Therefore, an optimization process is carried out to determine the most suitable geometrical dimensions that enhance the sensing performance of the device. Key parameters such as the lattice constant, air-hole radius, and cavity dimensions play a significant role in controlling the optical properties of the photonic crystal structure. By carefully adjusting these parameters, it is possible to achieve strong light confinement within the cavity and improve the interaction between the electromagnetic field and the infiltrated analyte.

In this study, the optimization process focuses on achieving high sensitivity, a strong resonance peak, and a high-quality factor (Q-factor). Variations in the lattice constant and hole radius directly affect the photonic bandgap and the resonance wavelength, which are crucial for ensuring that the sensor operates near the telecommunication wavelength of 1.55 μm . In addition, the geometry of the cavity defect is optimized to maximize the localization of light in

the sensing region, thereby increasing the sensor's ability to detect small refractive index changes associated with biological samples.

Through systematic parametric analysis and numerical simulations, the optimal structural parameters are identified. These optimized parameters provide a balance between optical confinement, sensitivity, and stability of the resonance signal, enabling the proposed photonic crystal biosensor to achieve improved performance for biomedical sensing applications, including early vitiligo detection.

III.4 Photonic Crystal Cavity Configuration: Structures with and without Ring Cavity

Two photonic crystal cavity configurations are investigated to evaluate their effect on the sensing performance of the proposed biosensor for vitiligo detection. The first structure consists of a photonic crystal lattice with a waveguide and a central defect without a ring cavity, where light propagates through the structure with limited electromagnetic field confinement, resulting in moderate interaction with the analyte. To improve the sensing performance, a second configuration incorporating a ring cavity defect is introduced. The ring cavity enhances the localization of the optical field within the sensing region, increasing the interaction between the optical field and the analyte. This leads to a more noticeable resonance wavelength shift when changes in the refractive index occur. By comparing the two configurations, the impact of the ring cavity on optical confinement and sensor sensitivity can be clearly demonstrated, highlighting its effectiveness for early vitiligo detection.

III.4.1 Photonic Crystal Structure without Ring Cavity

Figure III.2 illustrates the first configuration of the proposed photonic crystal sensor, designed without a ring cavity defect. The structure consists of a two-dimensional photonic crystal lattice formed by a periodic arrangement of air holes embedded in a silicon slab. The air holes are distributed in a regular pattern to create a photonic crystal that enables strong control of light propagation through the structure. The overall lattice contains a large number of holes arranged in a square domain, providing a sufficient photonic crystal area for efficient light confinement.

A straight waveguide is created by removing a row of air holes along the horizontal direction, allowing the optical signal to propagate through the photonic crystal. The input optical source is positioned on the left side of the structure, while the output port is placed on the right side to collect the transmitted signal. In this first design, a single circular defect cavity is introduced at

the center of the structure along the waveguide to locally modify the refractive index distribution and slightly perturb the propagation of light.

However, since the cavity does not have a ring configuration, the localization of the electromagnetic field remains limited compared to resonant ring structures. Consequently, the interaction between the optical field and the surrounding analyte is relatively weak, resulting in moderate sensing performance. This configuration, therefore, serves as a reference structure, which will later be compared with the optimized design incorporating a ring cavity to demonstrate the improvement in optical confinement and sensor sensitivity.

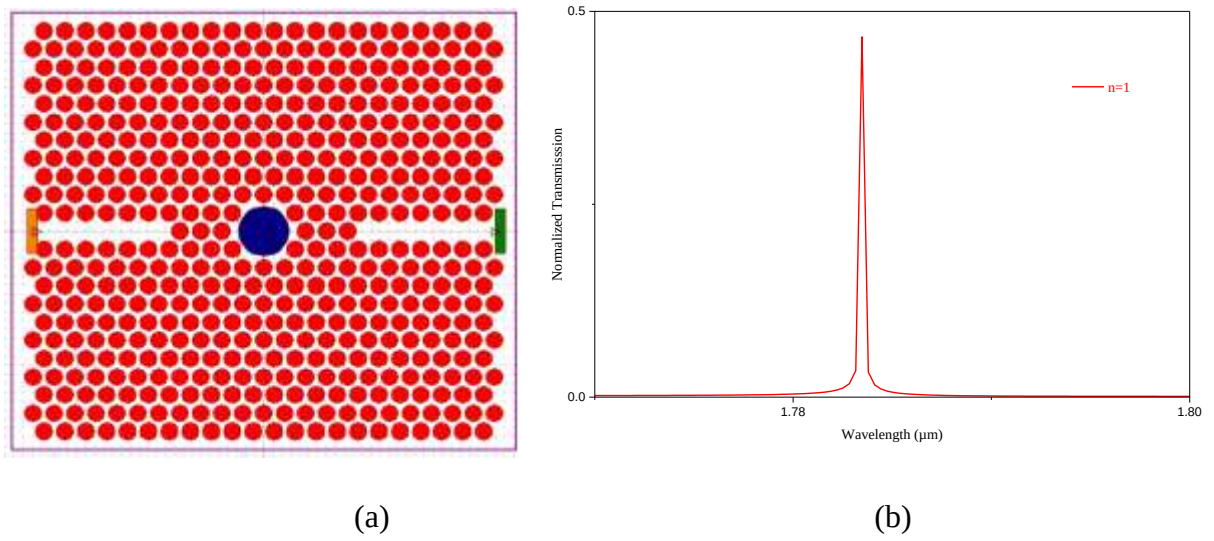


Figure III.2. (a) Structure model of the first biosensor based on a microcavity coupled to two waveguides, where the cavity radius $R=1.2a$. (b) Normalized transmission spectrum for the proposed design for $n=1$.

III.4.2 Photonic Crystal Structure with Ring Cavity

Figure III.3 shows the proposed two-dimensional photonic crystal biosensor incorporating a ring cavity defect. The structure consists of a periodic array of air holes etched in a silicon slab forming a photonic crystal lattice. A line defect waveguide is created by removing a row of air holes along the horizontal direction to allow light propagation from the input source located on the left side toward the output port on the right side. At the center of the structure, a ring-shaped cavity is introduced by modifying the geometry of the holes around a central region, forming a circular resonant cavity.

The ring cavity acts as a resonant sensing region, where the optical field becomes strongly localized. This strong confinement enhances the interaction between the propagating light and the analyte introduced into the cavity. When the refractive index of the analyte changes, the resonant wavelength of the cavity shifts, enabling sensitive detection. Due to this enhanced light–matter interaction, the ring cavity configuration significantly improves the sensitivity and detection capability of the photonic crystal sensor, making it suitable for early vitiligo detection applications.

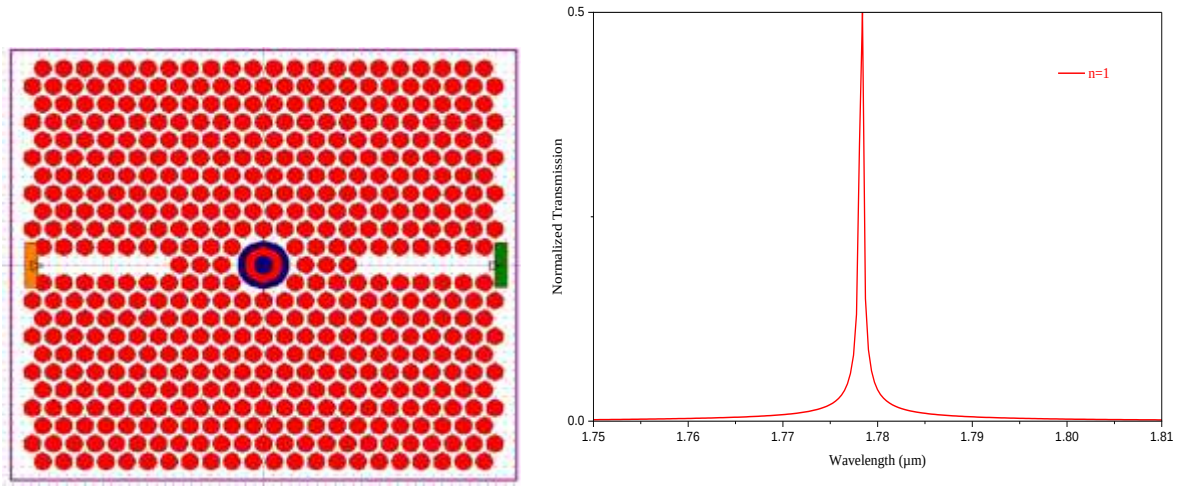


Figure III.3. (a) Structure model of the first biosensor based on a microcavity coupled to two waveguides, where the ring radius $R_{in}=0.21\mu\text{m}$ and $R_{out}=0.41\mu\text{m}$. (b) Normalized transmission spectrum for the proposed design for $n=1$.

III.4.3 Effect of Ring Cavity Inner Radius (R_{in}) on the Performance of the Proposed Biosensor

In this part of Chapter III, we study the effect of the ring cavity inner radius (R_{in}) on the overall performance of the photonic crystal device. R_{in} directly affects the resonant wavelength: increasing R_{in} enlarges the cavity, leading to a redshift of the resonance, while decreasing R_{in} tightens the mode confinement, producing a blueshift. R_{in} also strongly influences the Q-factor of the cavity; an optimal R_{in} reduces scattering and radiation losses, enhancing light confinement. Furthermore, R_{in} impacts the sensitivity of the device for biosensing applications, as it controls the overlap between the evanescent field and the target analyte. In the proposed structure for vitiligo detection, careful tuning of R_{in} allows precise control of the resonance wavelength and maximizes interaction with the affected skin regions, thereby improving detection accuracy and device efficiency.

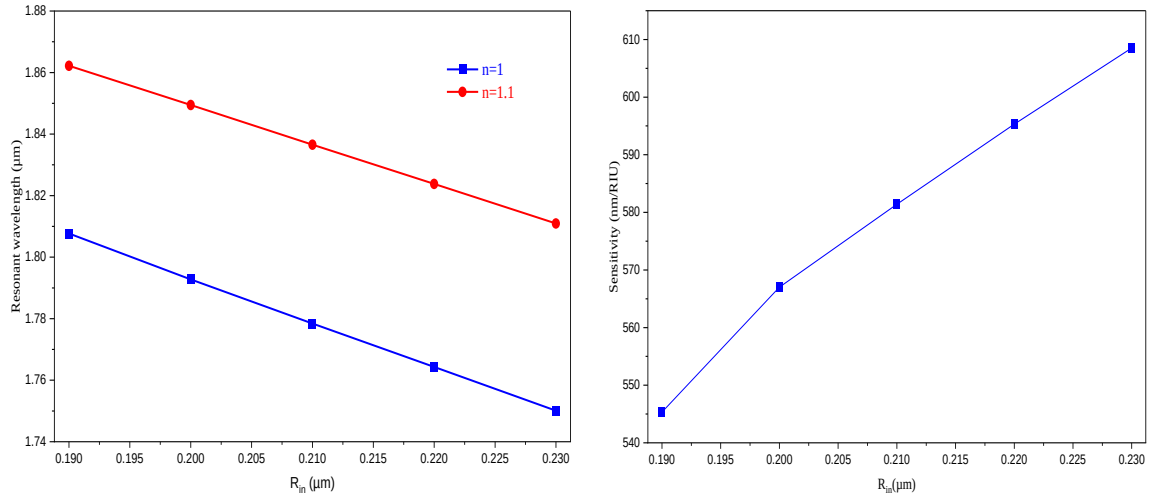


Figure III.4. The variation of the resonant wavelength and the sensitivity according to the inner radius R_{in} for $R_{out}=0.41\mu\text{m}$.

Table III.1 summarizes the variation of the resonant wavelength and the corresponding sensitivity as a function of the inner radius (R_{in}). The results show that as R_{in} varies, a noticeable shift in the resonant wavelength is observed, which directly affects the sensitivity of the proposed biosensor.

Table III.1. The values of resonant wavelength and sensitivity according to R_{in} .

R_{in} (μm)	Refractive index	Resonant wavelength (nm)	Sensitivity (nm/RIU)
0.19	$n=1$	1807.66	545.3
	$n=1.1$	1862.19	
0.20	$n=1$	1792.75	567
	$n=1.1$	1849.45	
0.21	$n=1$	1778.4	581.4
	$n=1.1$	1836.54	
0.22	$n=1$	1764.28	595.3
	$n=1.1$	1823.81	
0.23	$n=1$	1750.08	608.5
	$n=1.1$	1810.93	

III.4.4 Effect of Ring Cavity Outer Radius (R_{out}) on the Performance of the Proposed Biosensor

Figure III.4 illustrates the influence of the ring cavity outer radius (R_{out}) on the performance of the proposed 2D-PhC biosensor. As shown in Figure III.4(a), the resonant wavelength increases quasi-linearly with increasing R_{out} for both refractive index ($n = 1$ and $n = 1.1$), indicating that enlarging the cavity effectively shifts the resonance toward longer wavelengths. In contrast, Figure III.4(b) shows that the sensor sensitivity decreases as R_{out} increases, from approximately 680 nm/RIU to about 570 nm/RIU. This inverse relationship suggests that smaller cavity dimensions provide stronger confinement of the optical mode and higher refractive index responsiveness. Overall, these results highlight that optimizing R_{out} is critical to achieving a compromise between resonance tunability and maximum sensing performance.

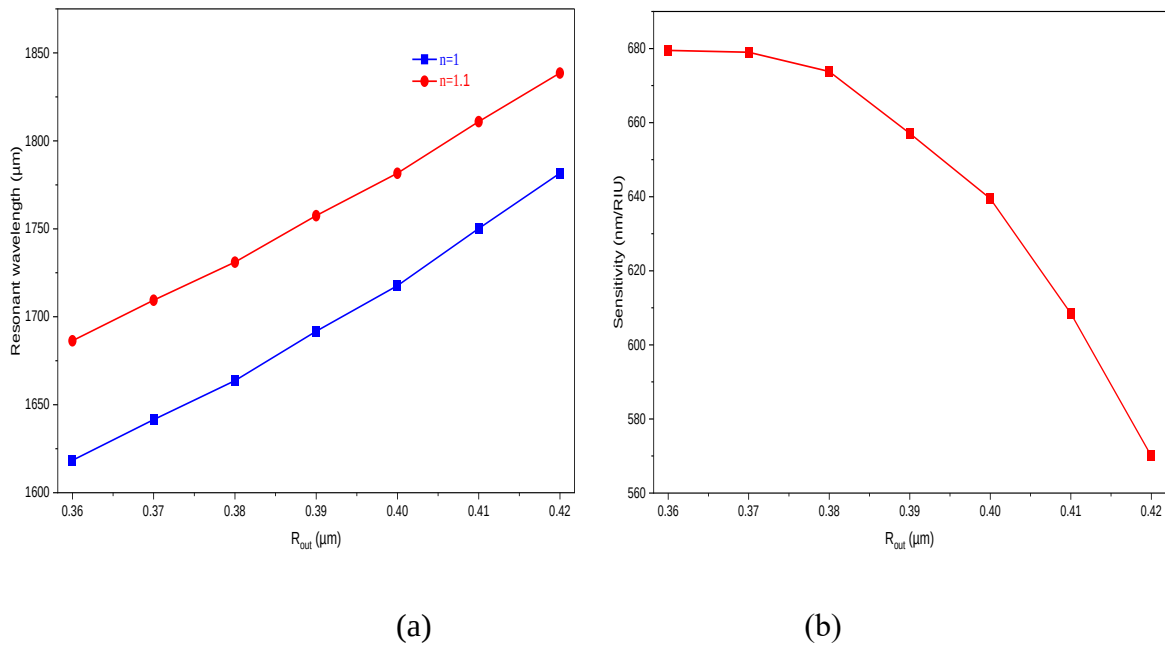


Figure III.4. The variation of the resonant wavelength and the sensitivity according to the outer radius R_{out} for $R_{in}=0.23\mu\text{m}$.

Table III.2 presents the variation of the resonant wavelength and the corresponding sensitivity as a function of the outer radius (R_{out}). The obtained results indicate that the resonant wavelength exhibits a clear shift with changes in R_{out} , which is also reflected in the variation of the sensor sensitivity. This confirms that the outer radius is an important design parameter to optimize and enhance the sensing performance of the device.

Table III.2. The values of resonant wavelength and sensitivity according to R_{out} .

R_{out} (μm)	Refractive index	Resonant wavelength (nm)	Sensitivity (nm/RIU)
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0.36	n=1	1618.38	679.5
	n=1.1	1686.33	
0.37	n=1	1641.49	679
	n=1.1	1709.39	
0.38	n=1	1663.61	673.8
	n=1.1	1730.99	
0.39	n=1	1691.75	657.1
	n=1.1	1757.46	
0.40	n=1	1717.62	639.5
	n=1.1	1781.57	
0.41	n=1	1750.08	608.5
	n=1.1	1810.93	
0.42	n=1	1781.57	570
	n=1.1	1838.57	

III.5 Sensing Mechanism for Early Vitiligo Detection

Vitiligo is an acquired depigmenting disorder characterized by the selective destruction or functional impairment of melanocytes, resulting in well-demarcated achromic macules and patches on the skin [5,6]. Although the condition is not life-threatening, it has significant dermatological and psychosocial implications, particularly in individuals with higher baseline skin pigmentation [7]. Additionally, the absence of melanin in affected regions increases susceptibility to ultraviolet (UV)-induced damage, including sunburn and photoaging. Epidemiological studies estimate a global prevalence ranging from 0.1% to 2%, with no significant predilection for sex or ethnicity [8].

The pathogenesis of vitiligo is multifactorial and remains incompletely elucidated. Current evidence supports a complex interplay of genetic susceptibility, autoimmune dysregulation, oxidative stress, and inflammatory pathways leading to melanocyte degeneration. Autoimmune mechanisms, particularly cytotoxic T-cell-mediated responses against melanocyte-specific antigens, are considered central to disease progression. Concurrently, elevated reactive oxygen species (ROS) levels and impaired antioxidant defense systems contribute to melanocyte apoptosis and dysfunction. However, the relative contribution of these mechanisms varies among patients and continues to be an area of active investigation [6].

At the molecular level, vitiligo is primarily associated with the depletion of melanin, the biopolymer synthesized by melanocytes that determines skin pigmentation and provides photoprotection by absorbing and dissipating UV radiation. While structural components such as keratin, collagen, and the epidermal–dermal architecture are essential for overall skin integrity, they are not directly implicated in the depigmentation process. Instead, melanocyte loss and subsequent melanin deficiency remain the defining features of the disorder [6,9].

In this final chapter, a photonic crystal–based optical biosensor is presented as a promising approach for the detection and diagnosis of vitiligo, while the broader application of photonic techniques provides a powerful paradigm for its noninvasive, efficient, and longitudinal monitoring [6,9,10].

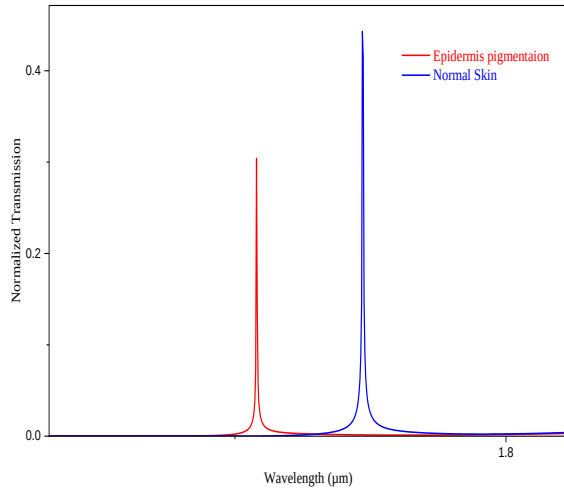
Table III.3 presents the refractive indices of normal and vitiligo-affected skin as reported in [6].

Table III. 3. Refractive index of normal and affected-vitiligo skin [10].

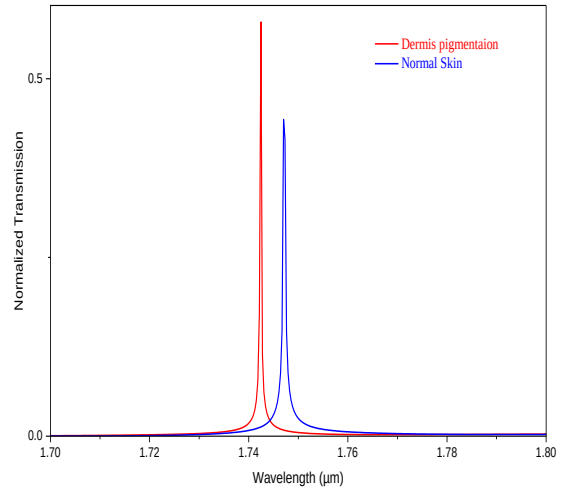
Sample details	Refractive index
Epidermis	1.34
Dermis	1.41
Normal skin	1.42
Collagen	1.43
Keratin	1.51
Melanin	1.72

Figure III.5 illustrates the normalized transmission spectra as a function of wavelength for normal skin ($n = 1.42$) compared with various pigmented skin constituents exhibiting distinct refractive indices. In Figure. III.5(a), the contrast between normal skin and epidermis-pigmented tissue ($n = 1.34$) induces a noticeable spectral shift due to the reduced refractive index. A smaller variation is observed in Figure. III.5(b) for dermis-pigmented skin ($n = 1.41$), where the refractive index is close to that of normal tissue, resulting in minimal resonance displacement. In contrast, Figure. III.5(c) shows a slight redshift for collagen-pigmented skin ($n = 1.43$), while a more pronounced shift is evident in Figure. III.5(d) for keratin-pigmented skin ($n = 1.51$), reflecting the higher refractive index contrast. The most significant spectral shift is observed in Figure. III.5(e) for melanin-pigmented skin ($n = 1.72$), highlighting the strong influence of melanin on the optical response. These results demonstrate the high

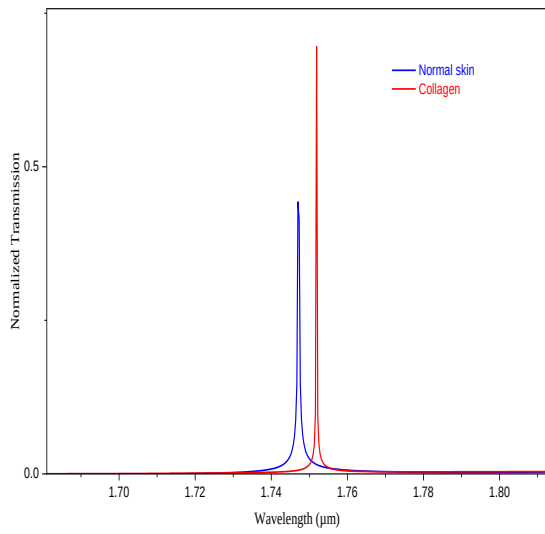
sensitivity of the photonic crystal sensor to refractive index variations, enabling effective differentiation between normal and vitiligo-affected skin tissues.



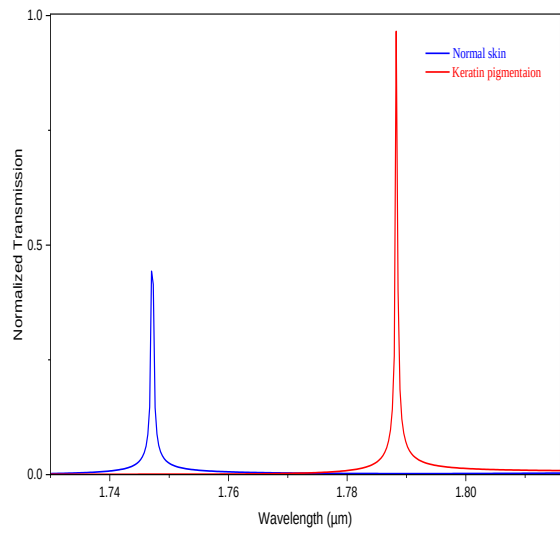
(a)



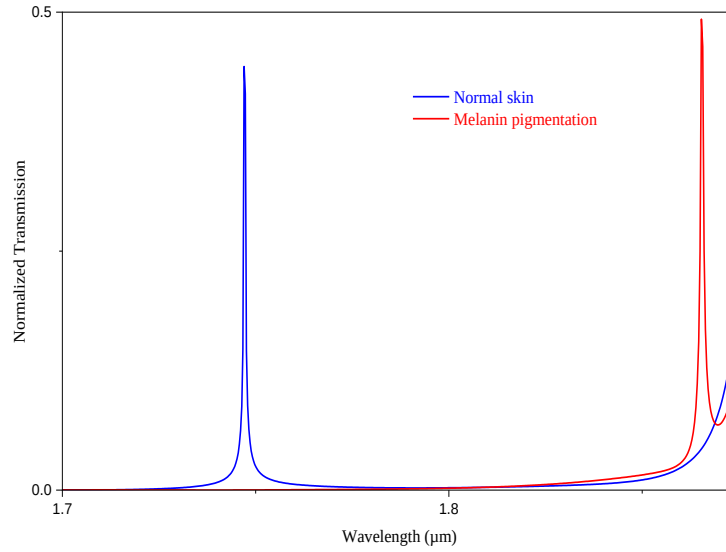
(b)



(c)



(d)



(e)

Figure III.5. Normalized transmission spectra as a function of wavelength **(a)** for normal skin ($n=1.42$) and epidermis-pigmented skin ($n=1.34$), **(b)** for normal skin and dermis-pigmented skin ($n=1.41$), **(c)** for normal skin and collagen-pigmented skin ($n=1.43$), **(d)** for normal skin and keratin-pigmented skin ($n=1.51$), **(e)** for normal skin and melanin-pigmented skin ($n=1.72$).

The results summarized in Table III.4 highlight the dependence of the photonic crystal sensor response on the refractive index of normal and vitiligo-affected skin tissues. A clear trend is observed in which an increase in refractive index leads to a progressive redshift in the resonant wavelength, ranging from $1.70793 \mu\text{m}$ for epidermis ($n = 1.34$) to $1.86532 \mu\text{m}$ for melanin ($n = 1.72$). The Q-factor exhibits significant variation, with exceptionally high values for dermis (1.3506×10^5) and melanin (6.4219×10^5), indicating strong optical confinement and low energy loss. In contrast, lower values, such as those for keratin (Q-factor = 1.3336), indicate reduced resonance quality. Sensitivity values remain relatively high across most samples, with a maximum of 490 nm/RIU observed for collagen, demonstrating the sensor's strong responsiveness to refractive index changes. Notably, normal skin ($n = 1.42$) shows an intermediate resonant wavelength of $1.74702 \mu\text{m}$, serving as a reference point for comparison, while deviations from this value in other samples enable effective differentiation. These findings confirm the high sensitivity and selectivity of the proposed sensor for distinguishing between normal and compositionally altered (vitiligo-affected) skin tissues.

Table III. 4. The values of resonant wavelength, Q-factor, and sensitivity for normal and vitiligo-affected skin.

Sample details	Refractive index	Wavelength (μm)	Q-factor	Sensitivity (nm/RIU)
Epidermis	1.34	1.70793	48.721	488.62
Dermis	1.41	1.74246	1.3506×10^5	456
Normal skin	1.42	1.74702	38.908	*
Collagen	1.43	1.75192	25940	490
Keratin	1.51	1.78826	1.3336	458.22
Melanin	1.72	1.86532	6.4219×10^5	394.33

III.6 Conclusion

In conclusion, Chapter III has presented a comprehensive analysis of the proposed photonic crystal-based biosensing approach for the differentiation of normal and vitiligo-affected skin. The study investigated the influence of refractive index variations associated with different skin components on the transmission spectra, resonant wavelength, Q-factor, and sensitivity of the designed sensor. The obtained results demonstrate a clear correlation between refractive index changes and spectral response, enabling precise optical discrimination between healthy and depigmented tissues. High sensitivity and pronounced resonance shifts confirm the capability of the structure to detect subtle biochemical and structural variations in skin composition. Overall, the findings of this chapter validate the effectiveness of the proposed photonic crystal sensor as a promising tool for noninvasive vitiligo diagnosis and highlight its potential for future biomedical sensing applications.

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General Conclusion

General Conclusion

In this thesis, we have systematically investigated the enhancement of sensitivity in two-dimensional photonic crystal (2D PhC) sensor platforms for clinical diagnostic applications, with a specific focus on the detection of vitiligo. The growing need for non-invasive, label-free, and early diagnostic tools for autoimmune skin disorders motivated this research, given the limitations of conventional methods such as visual inspection under Wood's lamp and invasive skin biopsies.

The study began by exploring the fundamental principles of photonic crystals and optical sensing, emphasizing the role of the photonic bandgap (PBG) and defect-induced localized resonant modes. It was demonstrated that structural parameters—including lattice constant, hole radius, rod thickness, and defect configuration—critically influence the sensitivity, quality factor (Q), and figure of merit (FoM) of the proposed biosensor.

Through numerical simulations using the finite-difference time-domain (FDTD) method and plane wave expansion (PWE) solver, an optimized 2D PhC structure was designed and analyzed. The results revealed that the engineered sensor platform exhibits significantly enhanced sensitivity to minute refractive index changes induced by cell's refractive index changes (Healthy and pigmented cells). The high Q-factor and low detection limit achieved confirm the suitability of the proposed design for precise and reliable biosensing.

The key contributions of this work are threefold. First, we have established a systematic design methodology for tailoring 2D PhC structures to maximize sensitivity. Second, we have demonstrated the potential of photonic crystal biosensors specifically for vitiligo detection, an area that has received limited attention in the literature. Third, we have provided a computational framework that can be extended to other dermatological and clinical diagnostic applications.

Despite these promising results, certain limitations should be acknowledged. The study is primarily simulation-based, and experimental validation through device fabrication and testing with real biological samples remains necessary. Additionally, factors such as temperature variations, non-specific binding, and fabrication tolerances need to be addressed in future work.

Future research directions include the integration of the proposed sensor into a portable, point-of-care diagnostic device, the exploration of three-dimensional photonic crystal structures for further sensitivity enhancement, and the application of the same platform to detect other skin diseases, including melanoma, psoriasis, and atopic dermatitis.

In conclusion, this dissertation has successfully demonstrated that two-dimensional photonic crystal sensor platforms can be optimized to achieve enhanced sensitivity for clinical diagnostic applications. The proposed biosensor represents a promising, cost-effective, non-invasive, and label-free alternative for early vitiligo detection, paving the way for personalized and accessible healthcare solutions.

INVESTIGATION OF ENHANCED SENSITIVITY IN TWO-DIMENSIONAL PHOTONIC CRYSTAL SENSOR PLATFORMS FOR APPLICATION IN CLINICAL DIAGNOSTICS

Abstract : This study investigates the enhancement of sensitivity in two-dimensional photonic crystal (2D PhC) sensor platforms for clinical diagnostics, with a specific focus on vitiligo detection. Vitiligo, an autoimmune depigmentation disorder, requires early and accurate diagnosis, yet current methods remain subjective and invasive. By engineering periodic dielectric architectures and introducing structural defects, 2D PhCs create localized resonant modes within the photonic bandgap that are highly sensitive to refractive index changes caused by cells' refractive index changes (Healthy and pigmented cells). Using finite-difference time-domain (FDTD) simulations and plane wave expansion (PWE) methods, key parameters including the lattice constant, hole radius, quality factor (Q), and figure of merit (FoM) were optimized to maximize sensitivity. The results demonstrate a significantly enhanced sensing performance with a low detection limit, making the proposed platform a promising candidate for label-free, non-invasive, and point-of-care vitiligo diagnostics. This work contributes to the broader application of photonic crystal biosensors in dermatological and clinical settings.

Keywords: Photonic crystals, biosensor, Vitiligo, Optical Sensor, FDTD.

Résumé : Cette étude explore l'amélioration de la sensibilité de plateformes de capteurs à cristaux photoniques bidimensionnels (PhC 2D) pour le diagnostic clinique, en particulier la détection du vitiligo. Le vitiligo, une maladie auto-immune caractérisée par une dépigmentation de la peau, nécessite un diagnostic précoce et précis. Or, les méthodes actuelles restent subjectives et invasives. En concevant des architectures diélectriques périodiques et en introduisant des défauts structuraux, les PhC 2D génèrent des modes de résonance localisés au sein de la bande interdite photonique. Ces modes sont très sensibles aux variations d'indice de réfraction induites par les différences entre cellules saines et cellules pigmentées. À l'aide de simulations par différences finies dans le domaine temporel (FDTD) et de la méthode de développement en ondes planes (PWE), les paramètres clés — tels que la constante de réseau, le rayon des trous, le facteur de qualité (Q) et le facteur de mérite (FoM) — ont été optimisés afin de maximiser la sensibilité. Les résultats démontrent une performance de détection nettement améliorée, avec une faible limite de détection, faisant de la plateforme proposée une candidate prometteuse pour un diagnostic du vitiligo sans marquage, non invasif et réalisable au point de soin. Ce travail contribue à l'application plus large des biocapteurs à cristaux photoniques dans les contextes dermatologique et clinique.

Mot clé : cristaux photoniques, biocapteur, Vitiligo, Capteur Optique, FDTD.

المخلص: تبحث هذه الدراسة في تحسين حساسية منصات استشعار البلورات الضوئية ثنائية الأبعاد للتشخيص السريري، مع التركيز بشكل خاص على الكشف عن البهاق. البهاق وهو اضطراب مناعي ذاتي يُسبب فقدان التصبغ، ويتطلب تشخيصاً مبكراً ودقيقاً، إلا أن الطرق الحالية لا تزال ذاتية وجراحية. من خلال هندسة هياكل عازلة دورية وإدخال عيوب هيكلية، تُنشئ البلورات الضوئية ثنائية الأبعاد أنماط رنين موضعية ضمن فجوة النطاق الضوئي، وهي حساسة للغاية لتغيرات معامل الانكسار الناتجة عن تغيرات معامل انكسار الخلايا (الخلايا السليمة والخلايا المصبغة). باستخدام محاكاة المجال الزمني للفروق المحدودة (FDTD) وطرق توسيع الموجة المستوية (PWE) تم تحسين المعلمات الرئيسية، بما في ذلك ثابت الشبكة، ونصف قطر الثقب، وعامل الجودة (Q)، ومعامل الجدارة (FoM) لزيادة الحساسية إلى أقصى حد. تُظهر النتائج تحسناً ملحوظاً في أداء الاستشعار مع حد كشف منخفض، مما يجعل المنصة المقترحة مرشحاً واعداً لتشخيص البهاق دون استخدام علامات، وبطريقة غير جراحية، وفي نقاط الرعاية الصحية. يُسهم هذا العمل في توسيع نطاق استخدام أجهزة الاستشعار الحيوية البلورية الضوئية في المجالات الجلدية والسريرية.

الكلمات المفتاحية : بلورات ضوئية، مستشعر حيوي، مرض البهاق، مستشعر بصري، FDTD