



HIGH SENSITIVE 2D PHOTONIC CRYSTAL BIOSENSOR BASED ON HEXAGONAL RESONATOR COUPLED WITH A CAPSULE-SHAPED FOR THE DETECTION OF DEFERENT CANCEROUS CELLS

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ABSTRACT

In the present study, we introduce an innovative photonic crystal architecture meticulously engineered for biomedical applications, particularly optimized for biosensing functionalities. Our study focuses on meeting the increasing demand for quick, reliable, and easy-to-use detection methods in medical diagnostics. The proposed architecture employs a hexagonal arrangement integrated with two waveguides for signal input and output, which is further augmented by the inclusion of a pill-shaped resonator to enhance sensitivity. The design enables strong confinement of the electromagnetic field and improves interaction with the analyte. The simulations were performed using the Finite-Difference Time-Domain (FDTD) method over a wavelength range of 1.6 to 1.95 micrometers (μm). The findings indicate that the biosensor is capable of attaining a peak sensitivity of 571 nanometers per refractive index unit (nm/RIU), thereby underscoring its significant potential for detecting subtle alterations in biological specimens and contributing to the advancement of medical diagnostics. Such sensitivity levels demonstrate the effectiveness of the proposed structure in identifying biomolecular interactions and refractive index variations typically associated with various types of cancer cells and other biological conditions.



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I. INTRODUCTION

Photonic crystal biosensors have emerged as a promising platform in the field of optical sensing due to their high sensitivity, label-free detection capabilities, and potential for miniaturization [1]. These biosensors exploit the distinctive optical characteristics inherent to photonic crystals, which are composed of periodically arranged dielectric materials that govern light propagation [2]. By merging biomolecular interactions within these constructs, photonic crystal biosensors are equipped to perceive minute changes in the refractive index, thus allowing for the accurate detection of a diverse collection of biological entities including proteins, hormones, enzymes, viruses, nucleic acids, and pathogens [1],[3]. In recent decades, the evolution of all-optical devices has emerged as a pivotal trend within contemporary photonics, propelled by the demand for expedited, more efficient, and scalable systems for data processing and telecommunication.

Central to these breakthroughs are photonic crystals, which play a critical role in these advancements, offering versatile functionalities beyond biosensing [4]. Photonic crystal structures have been utilized as filters [5],[6], decoders [7],[8], logic gates [9] and sensors [10],[11]. In the realm of biosensing, photonic crystal sensors have demonstrated remarkable success in medical diagnostics, detecting biomarkers for diseases such as cancer [12], blood sugar [13] and temperature [14]. This paper will explore a new crystal photonic sensor that could be used as a cancer sensor. The finite difference time domain (FDTD) method was used to simulate the proposed designs and to investigate numerical results. The rest of the paper is structured as follows: In section II, the structure design is presented. Section III is reserved to the results and analysis followed by the application examples, comparison result, and validation in section IV. Finally, conclusion and perspectives are shown in Section V.

II. STRUCTURE DESIGN

The proposed biosensor is composed of 2D triangular lattices, with the size of the PhC structure measuring 21×19 . The lattice constant (a) is set at $0.47 \mu\text{m}$, and the radius of the air holes (r) is $0.19 \mu\text{m}$. The refractive index of the silicon slab is $n_{\text{si}} = 3.45$. In the initial design, the biosensor features two waveguides, created by removing a single row of air holes along the ΓK direction. A hexagonal cavity is placed at the center of the biosensor on both sides to maximize output transmission. This cavity is formed by eliminating eight holes on the left and right sides in the 10^{th} row, and seven holes in the center, shaping a hexagonal structure as depicted in Figure 1(a). To analyze the proposed biosensor, 2D Plane Wave Expansion (2D-PWE) and Finite-Difference Time-Domain (FDTD) methods were utilized. The photonic bandgap (PBG) of the designed photonic crystal (PhC) structure, without any defects, ranges from $\omega_1 = 0.2501$ (a/λ) to $\omega_2 = 0.41325$ (a/λ), covering a significant bandgap in the wavelength range of $1.1373 \mu\text{m}$ to $1.8792 \mu\text{m}$ for a TM-polarized wave. This was calculated using the 2D-PWE method in BandSolve software as shown in Figure 1(b).

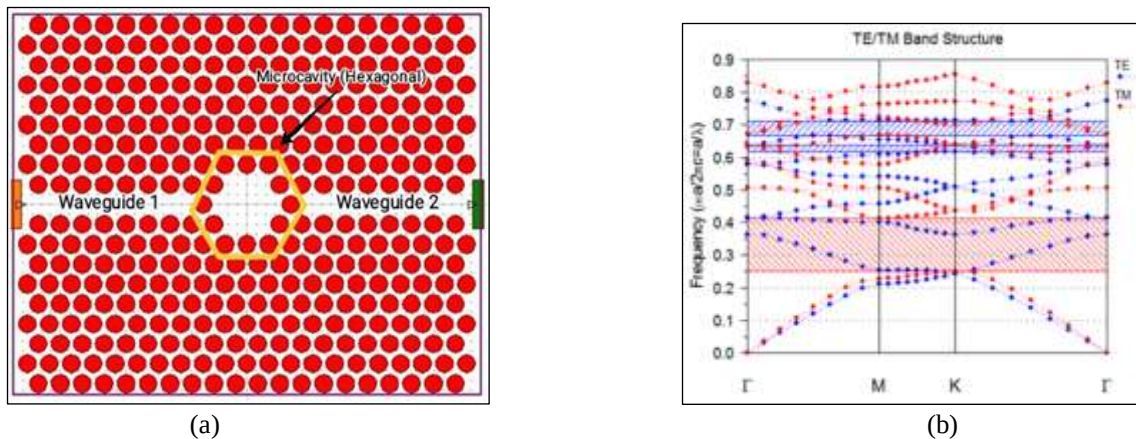


Figure 1: (a) Schematic of the first proposed 2D-PhC biosensor. (b) Band structure of the proposed design.
Source: Authors, (2026).

III. RESULTS AND ANALYSIS

It is well-known that introducing defects into the periodic lattice structure of a PhC disrupts the regularity of its dielectric function. Thus, the waveguide 1 and 2 obtained by omitting a row of air holes in the photonic lattice in the ΓK direction is shown in Figure 1(a). These defects allow for the formation of guided modes, with frequencies falling within the PBG range [15]. In this biosensor, we excited the cavity's resonant modes by applying a Gaussian pulse of about $3.6 \mu\text{m}$ through the waveguide's input. To ascertain the sensitivity of the suggested biosensor, a power monitor was also installed at the end of the waveguide to track the trapped mode [16]. In Figure 2, the biosensor's transmission spectra is represented across three diverse refractive indices ($n = 1$, $n = 1.025$, $n = 1.05$), with a uniform difference of 0.025 between successive values. The results indicate that as the refractive index of the ambient medium is elevated, the resonance wavelength (λ_{res}) experiences a corresponding shift. Figure 3 (a)(b) illustrates the propagation of light through the cavity structure within the XZ plane. It becomes evident from this representation that the electromagnetic field is significantly confined within the hexagonal cavity, thereby rendering the system exceedingly sensitive to variations in refractive index due to the pronounced interaction between light and matter. Figure 4 shows the linearity relationship between the resonance wavelengths and the refractive indices for the first and second mode. Sensitivity (S) constitutes a critical factor in the design and evaluation of refractive index (RI) sensors predicated upon photonic crystal structures; it can be quantitatively expressed as $S = \Delta\lambda / \Delta n$ (nanometers per refractive index unit (nm/RIU)), wherein $\Delta\lambda$ signifies the variation in the peak resonance wavelength of the transmittance spectrum, while Δn indicates the alteration in the refractive index within the photonic sensor framework.

By maintaining all other parameters constant and incrementally augmenting the refractive index from $n = 1$ to $n = 1.05$, the sensitivity for the first mode approximates 132 nm/RIU, whereas for the second mode, it is approximately 182 nm / RIU.

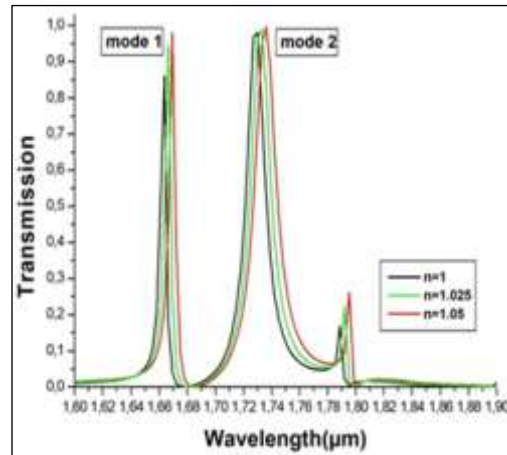


Figure 2: Transmission spectrum of the first proposed design as function of wavelength for different refractive indices.
Source: Authors, (2026).

In the second design and In order to improve the performance of our biosensor and increase its ability to detect small analyte concentrations and variations in the latter, we introduce the second iteration of a CPh biosensor predicated upon a hexagonal cavity integrated with a capsule. The aforementioned configuration provides a significant enhancement in both sensitivity and quality factor. The rationale for employing a capsule-shaped cavity characterized by an increased dimension is to promote the infiltration process, amplify light-matter interaction, and mitigate losses within the structural framework. Figure 5(a), shows that the capsule-shaped cavity is deliberately positioned in the middle part of the second proposed biosensor, with the capsule length L measured at 140 nm and the capsule radius R recorded at 190 nm. Figure 5(b) shows the transmission spectrum corresponding to a refractive index of $n = 1$ and the magnetic field distribution calculated using the FDTD method of the Fullwave software for the second proposed biosensor. As seen in Figure 5(b), when the cavity is in resonance, two sharp Lorentzian-shaped peaks appear inside the BIP at resonance wavelengths of 1.6566 μm for mode 1 and 1.8092 μm for mode 2.

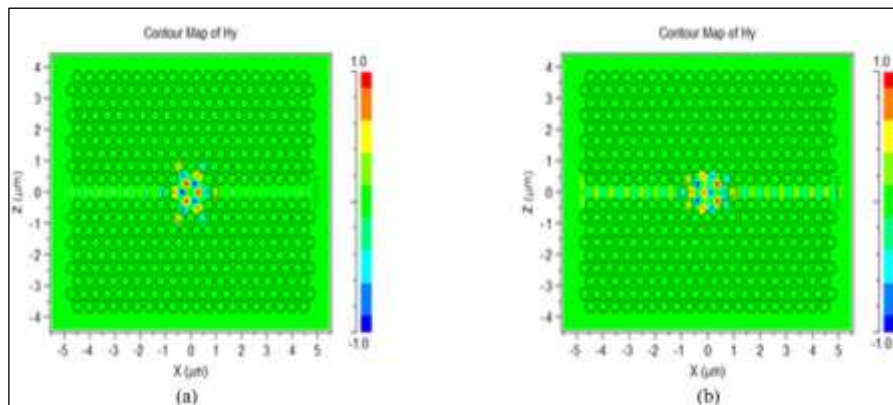


Figure 3: (a) Magnetic-field patterns with hexagonal cavity at $\lambda_1(\text{mode 1}) = 1.6637 \mu\text{m}$ (b) $\lambda_2(\text{mode 2}) = 1.7274 \mu\text{m}$.
Source: Authors, (2026).

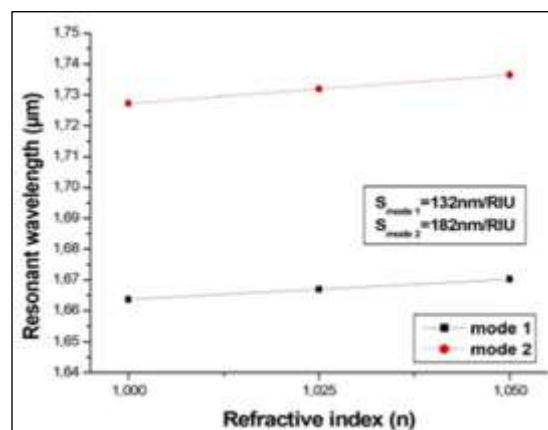


Figure 4: The resonance wavelength versus the refractive index n of the material under sensing.
Source: Authors, (2026).

The propagation characteristics of light within the cavity configuration, specifically in the (XZ) plane, are illustrated in Figures 6(a) and (b). Within this representation, it is distinctly observable that the electromagnetic field is significantly confined within the cavity region, exhibiting a greater intensity compared to the initial structure. This phenomenon renders the cavity exceptionally responsive to fluctuations in the refractive index, attributable to the pronounced light-matter interaction. The biosensor's transmission spectra are portrayed in Figure 7, showcasing three unique refractive indices ($n=1$, $n=1.025$, $n=1.05$) with a gradual increment of 0.025. It is observable that the variations in the resonance wavelength λ_{res} correspondingly amplify with the enhancement of the refractive index within the medium. The sensitivity associated with mode 1 approximates 256 nm/RIU, while mode 2 demonstrates a sensitivity of approximately 418 nm/RIU. It is crucial to acknowledge that the second design has a distinctly greater sensitivity than the first design. This enhancement is anticipated to be particularly relevant for biosensor applications where, for instance, biochemical reactions are monitored by detecting minimal fluctuations in refractive index within reaction environments. Figure 8 illustrates how the resonance wavelengths change in a linear pattern with the refractive indices for both the first and second modes. Furthermore, we will calculate and optimize the design's transmission and sensitivity by modifying the geometrical properties. First, the capsule length L is investigated. The value of L fluctuates from 100 to 260 nm at 40 nm intervals, while the other parameters stay constants at $R = 190\text{nm}$ and $r = 190\text{nm}$.

Afterward, a rigorous review was undertaken to understand how structural aspects contribute to defining an optimal layout for the biosensor. The impact of the capsule length L is depicted in Figure 9(a), where in an increment in the value of L from 100 to 260 nm, in 40 nm intervals, correlates with a shift in the resonance wavelength. Figure 9(b) reveals that the relationship between sensitivity and the value of L exhibits a nearly linear correlation, with the optimal sensitivity attained at $L = 220$ nm. Furthermore, by raising the value of L , the sensitivity of the sensor can be increased. For example, in mode 1, the sensitivity is 343 nm/RIU; in mode 2, on the other hand, the sensitivity is 571 nm/RIU, which corresponds to a value of $L = 220$ nm; this is in contrast to the sensitivity of 210 nm/RIU in mode 1 and 312 nm/RIU in mode 2, where the value of L was 100 nm. Next, we examined how various R values affected the characteristics of the PhC refractive index sensor. L is fixed at 220 nm, which is the best value already obtained, for the upcoming analysis. The transmission spectra of index 1 are displayed in Figure 10(a) for values of R ranging from 150 to 210 nm in steps of 20 nm; a higher value of R corresponds to a longer resonance wavelength. Figure 10(b) illustrates that the relationship between sensitivity and value R is nearly linear, with the highest sensitivity being attained at $L = 190$ nm. Additionally, we can attain a higher sensitivity of the sensor by elevating the resistance value R for mode 1 to achieve 228 nm/RIU, while mode 2 shows a sensitivity of 371 nm/RIU due to R being equal to 190 nm; this is compared to the sensitivity statistics of 343 nm/RIU for mode 1 alongside 571 nm/RIU for mode 2 with a resistance value retained at 190 nm. Table 1 compares the sensitivity (S) for different reported photonic crystal sensors in literatures with ours.

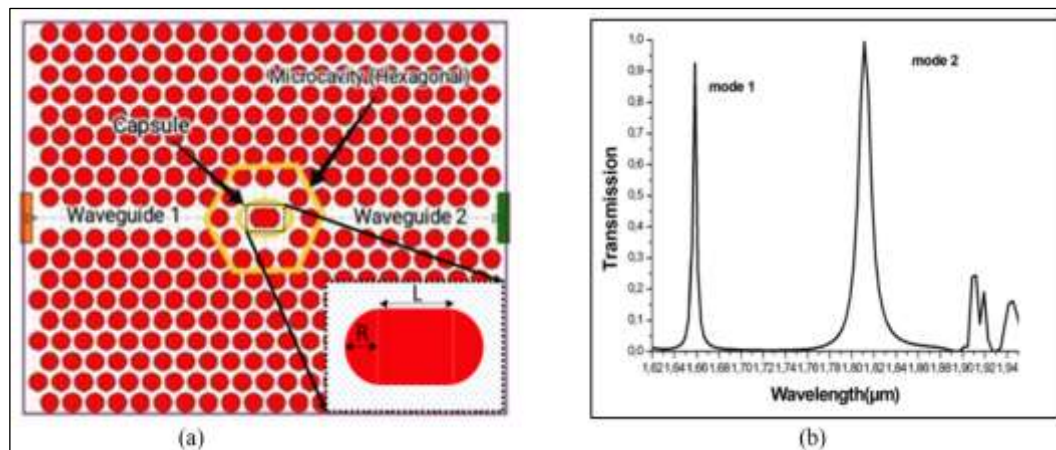


Figure 5: (a) Schematic of the second proposed 2D-PhC biosensor, (b) Transmission spectrum of the second proposed design as a function of wavelength for refractive indices $n=1$.

Source: Authors, (2026).

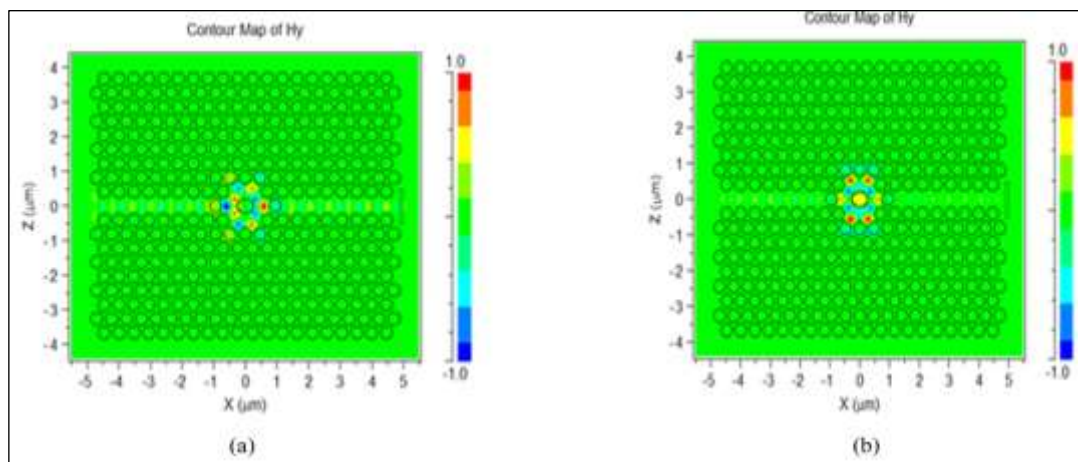


Figure 6: (a) Magnetic-field patterns with hexagonal cavity with capsule at λ_1 (mode1) =1.6566 μm , (b) λ_2 (mode2) =1.8092 μm .

Source: Authors, (2026).

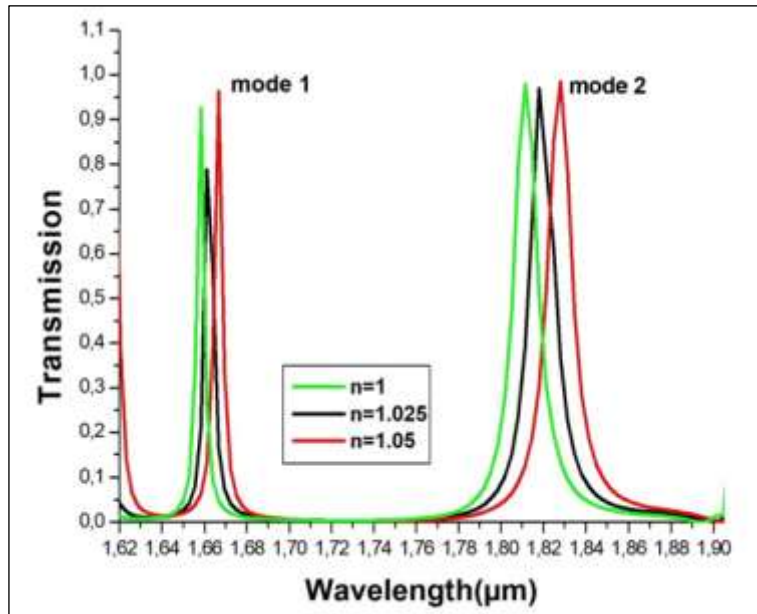


Figure 7: Transmission spectrum of the second proposed design as a function of wavelength for different refractive indices.
Source: Authors, (2026).

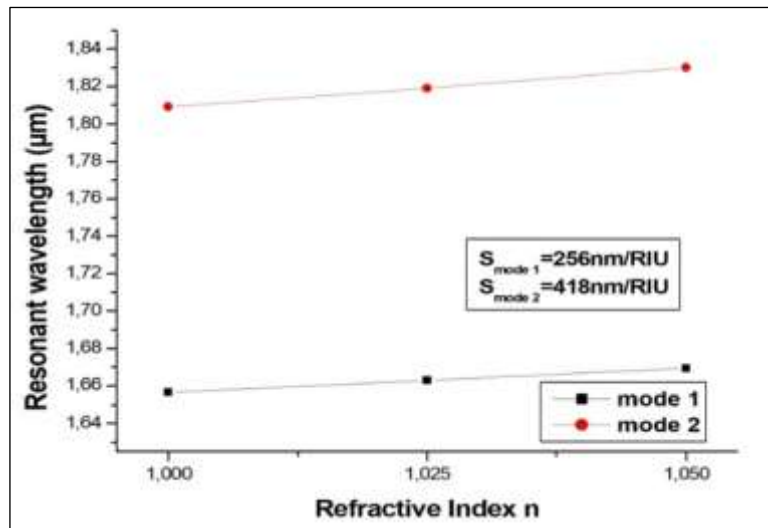


Figure 8: Resonance wavelength versus the refractive index n of the material under sensing.
Source: Authors, (2026).

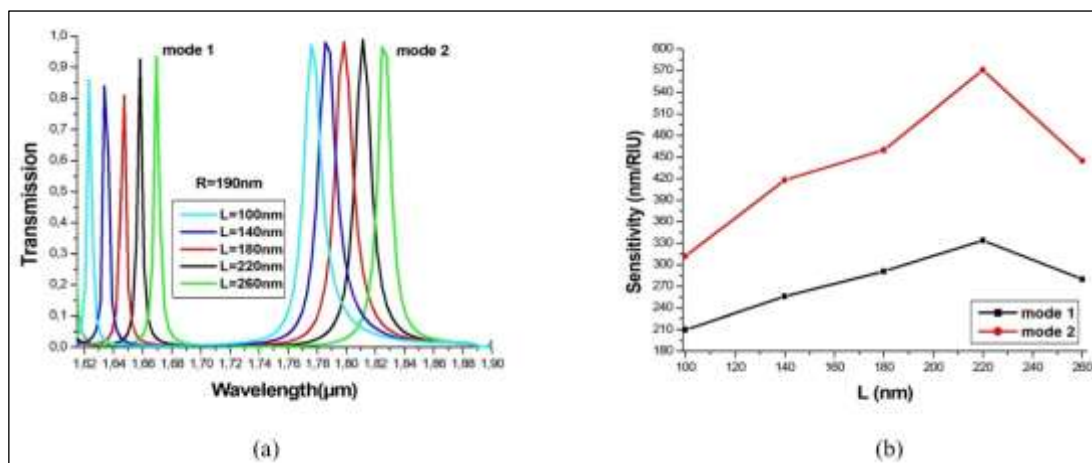


Figure 9: (a) Transmission spectra of the second proposed biosensor by L varying from 100 to 260 nm, (b) Sensitivity as a function of L .
Source: Authors, (2026).

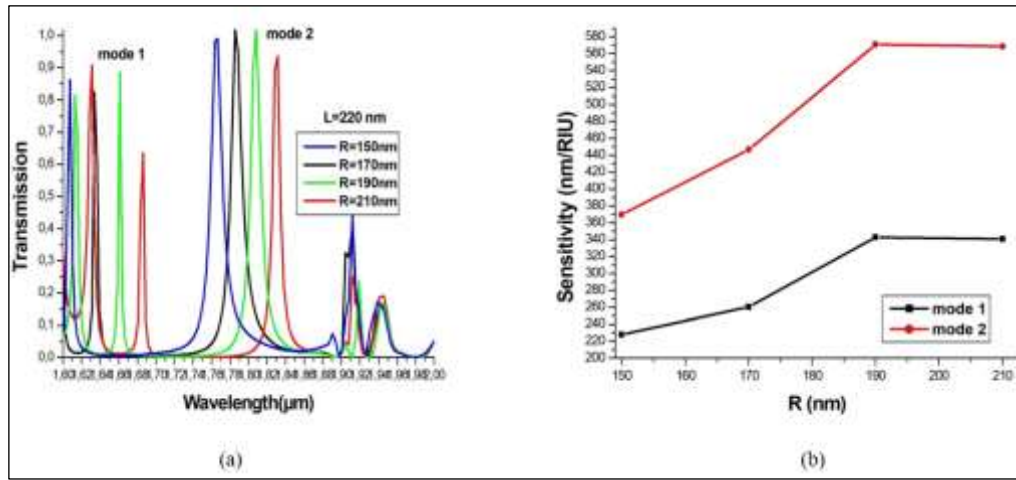


Figure 10: (a) Transmission spectra of the second proposed biosensor by R varying from 150 to 210 nm, (b) Sensitivity as a function of R. Source: Authors, (2026).

Table 1: Sensitivity comparison of different sensor structures.

Reference	Sensitivity (nm/RIU)	Year
[17]	425	2015
[18]	495.73	2021
[19]	357.22	2022
This work	571	2026

Source: Authors, (2026).

IV. APPLICATION EXAMPLE: CANCER SENSOR

As an illustration of how to use the most recent optimized structure (Fig. 5 (a), with $r = 190$ nm and $T = 220$ nm), we will investigate the cancer sensor. When cancerous cells start to proliferate in the human body, the specific cancerous cell's index of refraction (RI) becomes apparent [1]. The normal basal cells have a refractive index of 1.36, as cancerous cells start to proliferate within them, their index rises to 1.38. In Table 2, we have certain types of cancer and their RI "Jurkat (blood cancer), PC12 (adrenal gland cancer), and MCF-7 (breast cancer - type 2)" for healthy and affected cells [20],[21].

Table 2: Certain types of cancer and their RI.

Cell Name	Cell Type with Density Level	RI
Jurkat	Normal cell (30–70%)	1.376
	Cancerous (80%)T-shaped	1.390
PC12	Normal cell (30–70%)	1.381
	Cancerous (80%)	1.395
MCF-7	Normal cell (30–70%)	1.387
	Cancerous (80%)	1.401

Source: Authors, (2026).

The optimized biosensor's transmission, computed with 2D FDTD, is displayed in Figure 11. Curves for the refractive indices of the holes ($n = 1.36, 1.39, 1.395$, and 1.401) corresponding to several cancer cell types are obtained. (Jurkat, normal cell, PC12, MCF-7). They show how, when the holes' refractive index rises, the resonant peak moves towards longer wavelengths. It is well seen in Figure 12 that the refractive index changes versus the resonance wavelength for the first and the second mode are linear and the values of the sensitivity were optimized from 132 nm/RIU to 311 nm/RIU for the first mode and from 182 nm/RIU to 557 nm/RIU for the second mode highlighting the use of the capsule-shaped cavity positioned inside the hexagonal microcavity which gives a much better sensitivities. For Jurkat types, the resonant peak in mode 1 shifts by 9.24 nm for $\Delta n = 0.03$, so the sensor sensitivity can reach $S_{\text{mode1}} = 308$ nm/RIU. In mode 2, the shift is 16.5 nm for $\Delta n = 0.03$, resulting in a sensor sensitivity of $S_{\text{mode2}} = 550$ nm/RIU, and the transmission exceeds 95% in both modes. The sensitivity results of the optimized biosensor for different types of cancer cells are presented in Table 3.

Table 3: Sensitivity of the optimized biosensor for different types of cancer cells.

Cell Name	RI	Sensitivity (nm/RIU) Mode1	Sensitivity (nm/RIU) Mode2
Normal cell	1.36	/	/
Jurkat	1.39	308	550
PC12	1.395	313	562
MCF-7	1.401	311	559

Source: Authors, (2026).

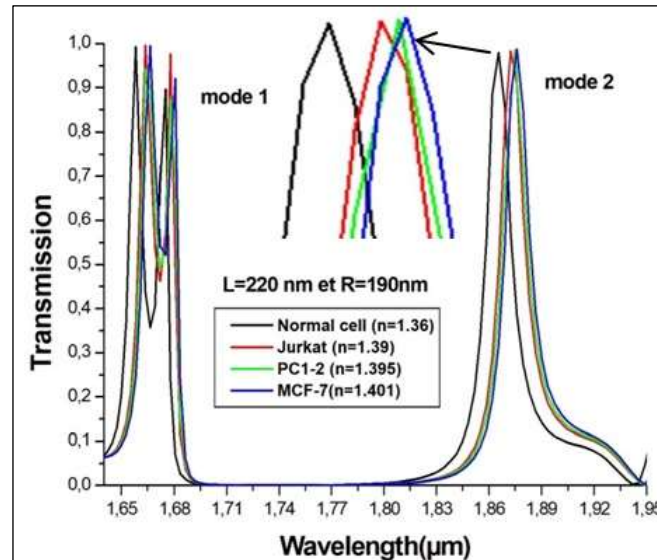


Figure 11: Transmission spectra for different Cancer cells.
Source: Authors, (2026).

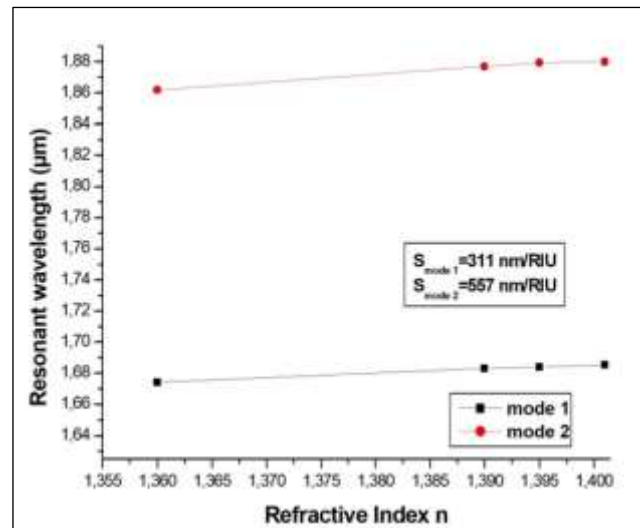


Figure 12: Resonance wavelength versus the refractive index n for different Cancer cells.
Source: Authors, (2026).

V. CONCLUSION

We present in this work, a new crystal photonic structure that used as a cancer sensor, the simulated result investigated using FDTD method and was assessed with comparison to other recent published works, our work has the highest sensitivity level reaching 571 nm/RIU; this design simplicity and compact size have a great potential to be used in all optical devices. As future work we will focus on the optimization of a design parameters in order to enhance sensitivity, quality factor, and also extending the detection of multiple cancer biomarkers in the sensor.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Hocine Bensalah, Wahiba Menasri, Abderrahmane Imam, Abdesselam Hocini, Mohammad Soroosh, Hocine Bahri, Hiba Bouandas, Imane Zegaar, Abdelhalim Tlemçani, Nadia Menasri.

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Investigation: Hocine Bensalah, Wahiba Menasri, Abderrahmane Imam, Abdesselam Hocini, Mohammad Soroosh, Hocine Bahri, Hiba Bouandas, Imane Zegaar, Abdelhalim Tlemçani, Nadia Menasri.

Discussion of results: Hocine Bensalah, Wahiba Menasri, Abderrahmane Imam, Abdesselam Hocini, Mohammad Soroosh, Hocine Bahri, Hiba Bouandas, Imane Zegaar, Abdelhalim Tlemçani, Nadia Menasri.

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Writing – Review and Editing: Hocine Bensalah and Wahiba Menasri.

Resources: Hocine Bensalah and Abdelhalim Tlemçani.

Supervision: Hocine Bensalah, Wahiba Menasri, Abderrahmane Imam, Hocine Bahri, Hiba Abdelhalim Tlemçani.

Approval of the final text: Hocine Bensalah, Wahiba Menasri, Abderrahmane Imam, Abdesselam Hocini, Mohammad Soroosh, Hocine Bahri, Hiba Bouandas, Imane Zegaar, Abdelhalim Tlemçani, Nadia Menasri.

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Data Availability: The data used in this study are publicly available from the Alzheimer's Disease Neuroimaging Initiative

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