

A new Design of High-sensitive Photonic Crystal Biosensor Based on Ring-shape Holes for Detecting Glucose Concentration

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Abstract - In this work an optical sensors has been designed and studied with different parameters to select the best result of Q factor and sensitivity; for that, we choose a 2D photonic crystal (PhC). The refractive index (RI) sensor is formed by a point-defect resonant cavity in the quasi-sandwiched waveguide with a hexagonal lattice of air holes. The properties of the sensor are simulated using a couple of two methods finite-difference time-domain method (FDTD) and the plane wave method (PWE). The calculation results show that a change in ambient RI is apparent; the sensitivity of the sensor is achieved.

The objective of our research was primarily modeling and optimization geometry of a first coupling path between a waveguide and a ring resonator with base of photonic crystals in order to improve the coupling properties in this structure.

It is in this context that we have exploited all the parameters already developed for improve the biodetection properties in a photonic crystal-based structure.

The role of our design is to sens small RI changes for detecting glucose concentration using resonant microcavity (RMC).

Index Terms -Biosensors, Cavity, Photonic crystals, Sensitivity, Quality factor, Resonance. FDTD, PWE.

I. INTRODUCTION

The simple, rapid and efficient detection of chemical or biological molecules has become a major challenge for the health, environment, agriculture, or even agro-food sectors, with increasingly demanding requirements. These have spawned the emergence of new technological solutions. In particular, on-chip integrated optical devices offer great potential for the development of transducers.

Generic, compatible with parallel detection, without markers of a wide variety of biomolecules and over a spectral range that can be adjusted from visible to infrared where absorption of many materials and biological noise are greatly reduced.

Their properties are mainly linked to the existence of forbidden bands which prevent the propagation of waves whatever the direction of the incident wave. These forbidden bands are used to create localized modes which confine optical

energy. By introducing a defect (point or linear or both) into these structures, the periodicity and therefore the continuity of the Photonic Band Gap (PBG) is broken and the propagation of light can be localized in the region of the defect.

The application of these photonic crystals as sensors constitutes a field of research which seems to be very promising due to their extreme miniaturization (0.1 mm² of detection surface), their high spectral sensitivity and the possibility of integrating them into MEMS. (Micro-Electro-Mechanical-Systems) The design of new photonic devices aimed at applications in various sectors of industry and high technologies, such as telecommunications (CP fibers), optoelectronics (lasers, photo detectors) and more recently bio-detection.

The detection phenomena are based on the high sensitivity of the localized modes appearing in the transmission spectra of photonic crystals via the variation of the refractive index of the analyte.

Two-dimensional microcavity photonic crystal sensors have both theoretically and experimentally demonstrated their ability to detect biochemical elements. Other authors have also proposed optical biosensors based on a CP waveguide. The sensors based on photonic crystal waveguides coupled with resonant cavities have many advantages such as compactness, high sensitivity, easy expansion to multi-channel sensors, various material choices and parallel measurement capability Recently, they have proved their aptitude for both theoretical and experimental detection, the latter is done by measuring the shift of the resonant wavelength in the transmission spectrum as a function of the change in the refractive index. .

Human health depends first and foremost on continuous biological monitoring. For this, the doctor is based on analyzes, most often blood, seeking to detect the presence but also to quantify biomolecules specific to diseases. These biomolecules are often either DNA that reveals genetic abnormalities or proteins, markers of disease. The most significant example concerns early diagnosis.

The more the bio detection will be sensitive, the more we detect a low concentration of these molecules and the more the probability of survival of the patient will be increased.

The uses of optical techniques in the context of bimolecular analyzes are very numerous. In this part, we present an overview of the different geometries of optical sensors used to measure refractive index variations for sensing applications, as well as a brief state of the art of their performance. The three most common configurations are: surface plasmon resonance (SPR) sensors, interferometry sensors and optical ring resonator sensors.

II. THEORETICAL AND DESIGN OF PROPOSED BIOSENSOR

In recent years, optical sensors which provide instantaneous detection and quantification of biological analytes have emerged of great interest, due to their promising characteristics such as: safety in flammable and explosive environment, immunity to electromagnetic interference, the rapidity of response and the ability to detect at a distance. Rapid advances in photonic technologies have dramatically improved detection performance, particularly in the areas of light-analyte interaction and device miniaturization. This has led to considerable improvements in the sensitivity and limit of detection (LD) of the sensor [1].

The principle of optical detection without label-free markers is based on the change one of the properties of light when it is in contact with the element of interest [2].

There are different detection methods for this, such as those exploiting the effects of changes in refractive index, absorbance property or non-linearity. Subsequently, we are only interested in detection based on the change of refractive index.

We have here a biosensor which has the ability to detect the glucose concentration [3].so an analysis has been performed to determine the parameters of the biosensor while the detection of glucose concentration in both normal and presence of glucose state, either with water or others aqueous solutions .

It formed by two-quasi waveguide and a ring cavity between their and the three are connected with a two punctual defect hole. So our coupling cavity-casiguide Phcs biosensor design is made using a hexagonal lattice of air holes with a refractive index $R_i = 1$ and radius of $r=0.38a$ (a is the period and equal to 550 nm) these holes are implanted in silicon (Si) slab (background) with $R_i=3.45$; her thickness is 200nm . the radius of two defect air hole is $R_d=0.3a$

The purpose of using quasi-guide is to pair the light in and out the cavity. And for a ring-shape holes is attend the maximum of confinement.

The number of holes is 17×17 , size of the structure is $92.65 \mu\text{m}^2$, The silicon dioxide (SiO_2) layer with R_i of 1.45 (low index) and a thickness of 1500 nm is used as support of silicon slab (high index) this is what give us a big imprisonment of light in the vertical direction which safeguarded by full internal reflection, so optical losses are

preventing accordingly thus the confinement in the cavity is enhanced. The values of radius' are $R_{in} = 0.22a = 121 \text{ nm}$ and $R_{out} = 0.45a = 247.5 \text{ nm}$, respectively.

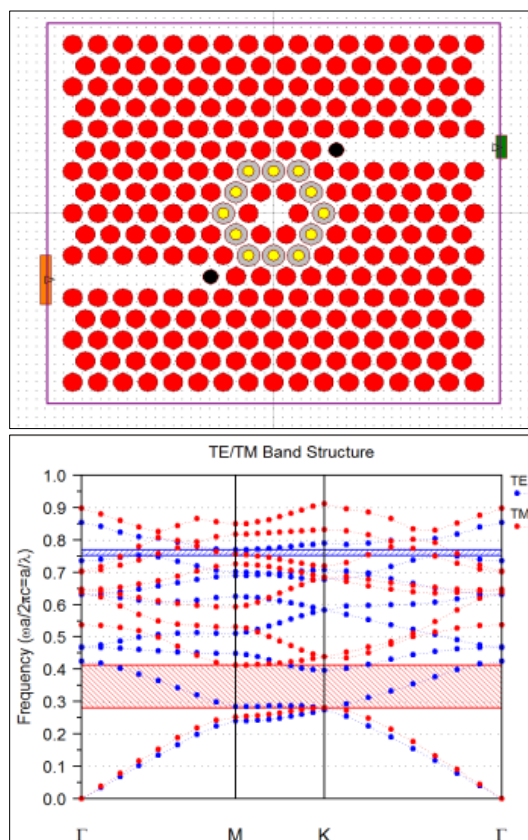


Fig. 1 Wavelength for the refractive index 1.33 glucose in the solution ($C = 0 \%$).

Thus, the ringed air region is given as: $R_{out} - R_{in} = 126.5 \text{ nm}$. The Si is a good candidate for PhC applications and the number of holes is 27.

Concerning the fabrication process of such structure lies in the ring's manufacture, which is composed of dielectric rods emerged in air holes. Säynätjoki et al. [4] demonstrated that a thin rin beam lithography.

To decrease the computational calculations that may occur in two-dimensional (2-D) structures, in dielectric medium having the effective RI of 2.868, which corresponds to the effective index of the central guided TM polarization mode in a 230 nm thick Si slab on SiO_2 at wavelength of 1550 nm. [5]

For the following numerical simulations, we applied the effective index approach given in references [6] and [7]. The dispersal properties of the systematic PhC structure have been analysed using the 2-D-PWE and FDTD method of Rsoft software[8].

For the TM polarization, The PBG of the fundamental structure without any defects calculated using PWE is depicted in Fig. 1. The basic structure has PBG for TM mode which is indicated by red region. As shown in Fig. 1, the normalized frequency is observed from $\omega_1=0.279$ to $\omega_2=0.409$, where λ is the vacuum wavelength, which is sufficiently wide for sensing region.

We have $\lambda=a/\omega$ so the broad so the PBG extends from wavelength range is $1334 \text{ nm} < \lambda < 1971 \text{ nm}$.

III. ANALYSES AND DISCUSSION

The biosensor is used to detect the glucose concentration over a range from 0 g/L to 60 g/L. The sensing principle is based on the change of the refractive index (RI) of the functionalized holes when the glucose concentration (C) varies and this is expression of them relation [8]:

$$n = 1.33230545 + 0.00011889 C \quad (1)$$

Where n is the refractive index and C the glucose concentration in g/L.

The different sensitivity and quality factor are with known glucose concentrations, displayed in table 1.

A Gaussian input light signal with a central wavelength of 1.55 in the glucose solution (C = 0 %). is launched into the input port of the inline quasi waveguide. The power monitor is placed at the end of the output port. The sensing mechanism is to detect the resonance wavelength, which is caused by the change of RI of the hole [10].

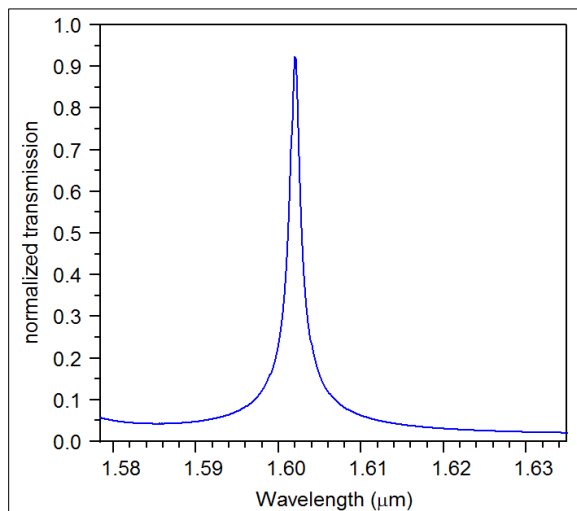


Fig.2: Wavelength for the refractive index 1.33 glucose in the solution (C = 0 %).

Figure 2 show resonant cavity radius by decreasing RC radius to $R_{in} < 2 \mu\text{m}$ can be concluded that detection of the sensor for different samples can be done both by using the wavelength of the resonator and the transmissions power.

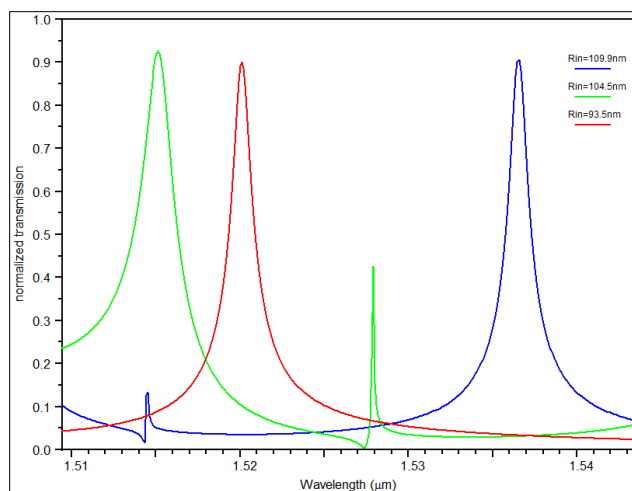


Fig. 3: The resonance wavelength for difference value of Rin.

Fig.4 represents the resonant wavelength for in different concentration of glucose. Table I shows the sensitivity and the quality factor, Fig. 5, 6 represents the resonant wavelength in different medium, TABLEII and first graph illustrate the result.

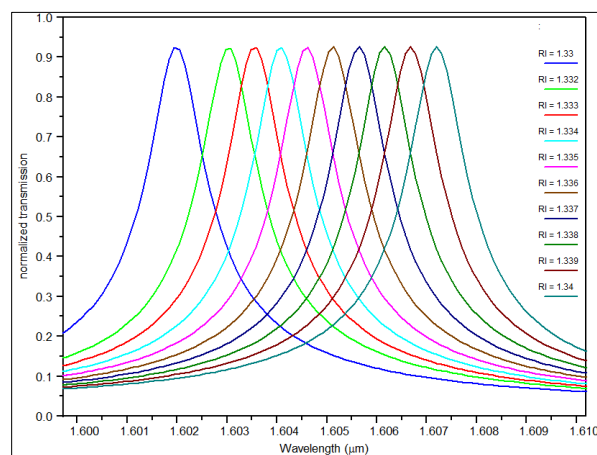


Fig. 4: Transmission spectrum in different concentration of glucose.

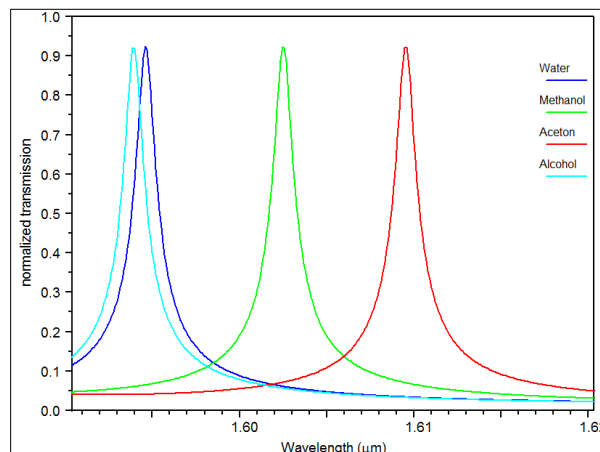


Fig. 5: Resonant wavelength for in different precises medium.

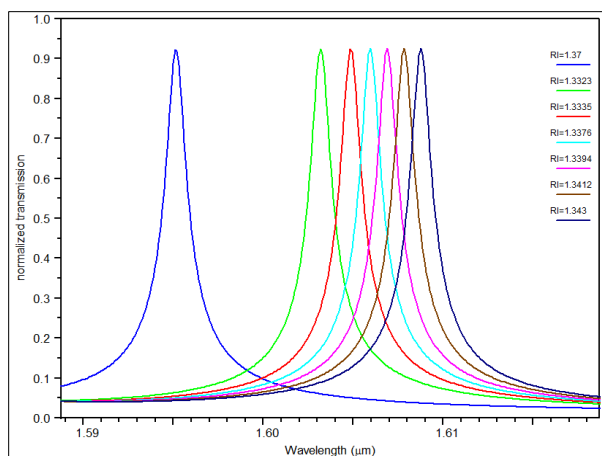


Fig. 6: Resonant wavelength for in different random medium.

Avital parameter in evaluating the performance of the designed sensor is the sensitivity (S) unit of nm/RIU which is defined as:

$$S = \Delta\lambda / \Delta n \quad (2)$$

λ_0 : The resonance frequency which is the output signal [11].
 $\Delta\lambda$: The difference between the resonant frequencies of the two successive output signals and Δn is the change in the RI.
 $\Delta\lambda$ is the difference of two RI value.
 S is measured in terms of another quantity used to describe the sensing capability of a sensor is quality factor.
 (Q) is defined as the ratio of stored and losses energy.

$$Q = \lambda_0 / \Delta\lambda \quad (3)$$

$\Delta\lambda$ is the full width at half maximum of the output signal [12,13].

Table 1

Sensor parameters changes for various value of glucose concentration

C(g/l)	Refractive index RI	wavelength λ (nm)	Q factor	sensitivity S (nm/RIU)
0	1.33	1602.0		
0	1.332	1603.1	890.611	500.000
0.10	1.333	1603.6	844.000	500.000
0.20	1.334	1604.1	891.167	500.000
0.30	1.335	1604.6	891.444	500.000
0.35	1.336	1605.1	891.722	600.000
0.40	1.337	1605.7	845.105	500.000
0.50	1.338	1606.2	892.333	500.000
0.60	1.339	1606.7	892.611	500.000
0.70	1.34	1607.2		

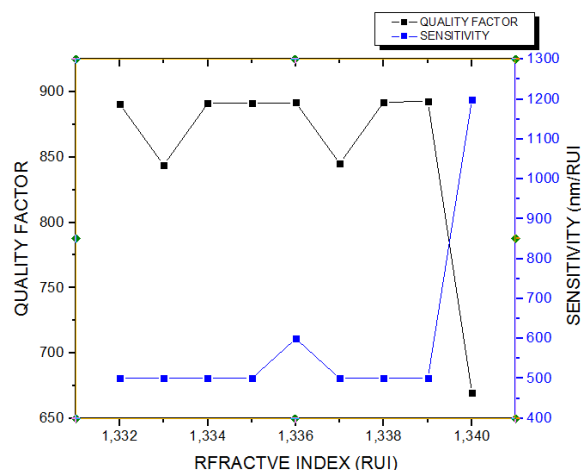


Fig. 8: variation of quality factor and sensitivity with difference values of RI.

From Fig. 8 conclude that sensitivity and quality factor are inversely proportional so it difficult to best result for both.

TABLE II. Sensor parameters changes in various mediums

Refractive index RI	wavelength λ (nm)	Q factor	sensitivity S (nm/RIU)
1.33	1602		
1.316	1594.6	938.000	526.667
1.331	1602.5	890.278	6851.852
1.3445	1695	190.449	3392.617
1.3147	1593.9		

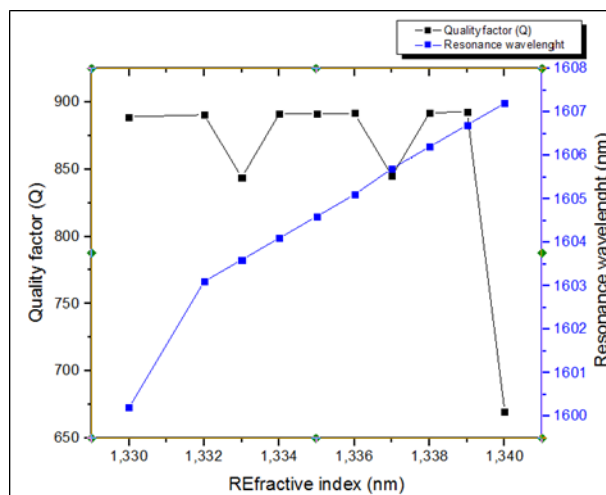


Fig. 9: variation of quality factor and resonance wavelength with difference solutions

From Fig. 9: we assume that the refractive index is directly proportional with the resonance wavelength almost in quasi-linearly way and inversely proportional with quality factor in a random way, so the transmission is decrease when refractive index increase.

It realized from last figure that the resonant wavelength varies linearly with the measurements of the different concentration of glucose.

In order to observe the effect of the inner radius (rin) of the cavity holes on the resonant wavelength for $C = 0 \text{ %g/L}$, we vary the inner radius from 0.11a to 0.22a. Figure 3 show that resonant mode is influenced by the change of rin, and we find that 0.22a is the high transmission.

In order to analyze the parameters of our design a, we change the RI of the air hole's extern rings from 1.33 to 1.34 according to equation (1). Fig. 4 illustrates that the resonance peak located at 1604,1 nm the spectrum of transmission obtained when glucose concentration varying from 0 g/l to 60 g/l. It is inferred from this figure that the resonant wavelength increases with increasing RI. The best result is $S=600$ and $Q=891.7$.

In order to identify if our biosensor could be operated as an optofluidic biosensor for detecting the glucose concentration in aqueous solution; as we see in Fig. 5 and TABLE II we infer that the resonant wavelength increases with increasing RI. And the value of sensitivity and quality factor increase by contribution to our biosensors.

From the FDTD results, the designed structure sensitivity is equal to 600 nm/RIU and the quality factor reaches 892 in the RI range of 1.33 to 1.34.

The sensibility of the presented biosensor is better than that of some previous structures proposed in recent articles for detecting the glucose concentration [5,6,14]. The comparison of the existing sensing structures is displayed in TABLE III. But the quality factor which calculated with a theoretical method has a low value and it is justified by the fact that the study is on a low concentration of glucose this is what make a big dissipation of power while the sensing system work.

TABLE III. Comparison of our results with some recent works

Reference	Sensing structure	S (nm/RIU)	Q
[5]	Ring shaped holes	422	8.99×10^{-7}
[6]	Ring cavity and holes	462,61	1.112×10^5
[14]	A ring cavity and holes with waveguide	462	1.11×10^5
This work	A ring ship with two waveguide	600	800

IV. CONCLUSION

In this work we have presented a proposal design for 2D ring cavity hexagonal and a ring air holes drilled in SI slab, this biosensor is intended for detecting low glucose concentration in an aqueous solution. The detection parameters and spectral position of the resonante mode were determined by adjusting the inner radius of the ring holes as well as the RI. The result of our simulation shows that a change of RI gives us a good sensitivity which achieved 600nm/RIU.

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