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*In the name of God, the Compassionate, the Merciful*

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# Analysis of Protein Concentration Based on Photonic Crystal Ring Resonator

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**ABSTRACT— In this paper, homogeneous, wavelength shift biosensor is designed for sensing the protein concentration using two dimensional Photonic Crystal Ring Resonator (PCRR). The sensor is designed to monitor the protein concentration from 0% to 100%. The proposed sensor is composed of periodic Si rods embedded in an air host with a circular PCRR that is placed between the inline quasi waveguides. It is observed that the resonant wavelength of the sensor is shifted (0.9 nm) to higher wavelength while increasing the protein concentration (5%) as the protein has a unique refractive index for each level. With this underlying principle, the performance of the sensor is analyzed for different protein concentration.**

**KEYWORDS:** Optical biosensor, photonic crystal, photonic band gap, ring resonator, protein concentration

## I. INTRODUCTION

After the invention of biosensor by Clark and Lyons in 1962, optical sensing mechanisms receive considerable attention in the applications of chemical and biochemical sensors, since application like industrial process control, military, environment monitoring and medical diagnostics [1] require various kinds of biological and chemical sensors.

Different integrated biological and biochemical sensors have been designed and analyzed, such as those using directional couplers [2], Mach–Zehnder interferometers [3], Bragg gratings [4], and micro-ring resonators [5]. Generally, the sensing mechanisms are categorized into two main schemes. The first scheme is the detection of effective refractive index change in terms of homogeneous sensing, i.e., determined by refractive index modification of covered medium. The second scheme is surface sensing, i.e., interfered by changing the position of group of rods in a periodic structure or changing the shape of particular rod [6], [7].

Micro-ring resonators which consist of a ring resonator is positioned between two straight waveguides, have been reported as biosensors and biochemical sensors with good sensitivity due to high quality factor of resonant peak in output spectra [8],[9]. The bio-sensing mechanism is based on the effective refractive index of the resonator that is changed due to analytes binding on it. The refractive index change of ambient fluidics or biomolecules bound on the surface of ring waveguide leads to the variation of resonant condition in turn shifts the resonant wavelength. In order to enhance the sensitivity by improving the quality factor of micro-ring resonator, the reduction of ring radius is required. However, it results increase in bending loss and radiation loss in conventional dielectric micro-ring waveguide. On the other hand, Photonic Crystals (PCs) structure provided a good solution to enable extremist small ring resonator with ultra-low bending loss owing to the excellent light confinement [10].

Very promising ultra-compact devices for sensing applications can be obtained by composing PCs. Generally, PCs are patterned artificial materials with periodicity in dielectric constant in one, two or three dimensions, which can create a range of forbidden frequencies called Photonic Band Gap (PBG). The propagation of light within the band gap frequency range is prohibited [11] - [14]. The existence of PBG in PCs is more suitable for designing optical devices. The completeness of the periodicity and hence PBG can be disturbed by introducing the defects, which allow the guided modes to propagate inside this region. Among One Dimensional (1D) PCs, Two Dimensional (2D) PCs and Three Dimensional (3D) PCs, 2DPCs are receiving keen attention from the scientific community as they have attractive features including relatively easy fabrication, better confinement of light, efficient PBG calculation, effective control of spontaneous emission and easy integration compared to conventional devices.

Typically, there are two approaches are reported for optical sensing namely resonant wavelength detection/shift and intensity detection where the resonant wavelength detection and shift is preferred for sensing approach because the resonant peak of high quality factor enables high detection resolution. In the literature, initially, PC resonator sensors are integrated in micro-beams and micro-cantilevers for force and mechanical strain detection [15]-[21] and protein detection [22]-[24]. Secondly the resonant wavelength of PCs resonator sensors are extremely sensitive to a small refractive index change attributed to medium around hole surface. By using a 2DPC micro-cavity based resonator, the measurement of ambient induced refractive index change via sensing the resonant wavelength shift has been demonstrated [25]. So far, the PC based sensor for protein detection is reported using line defects alone [26-29] which could not able to detect the protein concentration properly. Hence the attempt is made here to design the sensor to detect protein concentration using photonic crystal ring resonator.

In this paper, circular Photonic Crystal Ring Resonator (PCRR) based sensor is designed to sense the protein concentration over the range from 0% to 100%. The sensing characteristics such as Q factor, resonant wavelength, passband width and output efficiency are investigated. The rest of the paper is arranged as follows: In Section II, the structure design of circular PCRR based sensor is presented. Sensing characteristics are analyzed in Section III. In Section IV concludes the paper.

## II. Design of Ring Resonator Based Sensor

The perfect square lattice 21 × 21 PC structure is considered for designing the sensor. The radius of the rod is 0.185 × a, where 'a' is the distance between any two nearest rods, called as lattice constant. The dielectric constant of the rod is 11.9716 (refractive index, 'n' is 3.46), which corresponds to the effective index of Si rods. The lattice constant is selected to be 540 nm. The size of the proposed sensor is 11.4µm * 11.4 µm. Typically, pillar based PCs have several advantages such as low out-of-plane losses, low propagation loss, easy fabrication, compatible with classical Photonic Integrated Circuits (PICs), and effective single mode operation due to defects based structure. Furthermore, pillar based PC devices can be electrically contacted, inherently avoid current spreading and heat is efficiently dissipated into the substrate. Hence, the sensor is designed using pillar based PCs [30], [31].

The dispersion (band) diagram reveals the PBG region and the electromagnetic waves that propagate inside the periodic 1×1 PC (unit cell) structure as shown in Fig. 1 where two TE (Transverse Electric) PBGs (blue region) are noticed and TM (Transverse Magnetic) PBGs are not found. It shows the first reduced PBG from 0.295 a/λ to 0.435 a/λ whose corresponding wavelength ranges from 1241 nm to 1830 nm and second PBG from 0.732a/λ to 0.754a/λ whose corresponding wavelength ranges from 716 nm to 737 nm. Here, TE polarization is considered as the PC has PBG exclusively for the TE polarization alone. The simulation parameters and its values are listed in the Table 1. Rsoft-Fullwave simulator is used in this present work.

Table 1. The Parameters and its Values Used for Sensor

| **Parameters** | **Values** |
|---|---|
| Radius of the Rod | 0.1µm |
| Lattice Constant | 540 nm |
| Refractive Index of Rod | 3.46 |
| Background Index | 1.34 (0% of Protein Concentration) |
| Size | 11.4 µm ×11.4 µm (21×21 rods) |
| PBG Range | 0.295/λ to 0.435 a/λ (1241 nm - 1830 nm) |

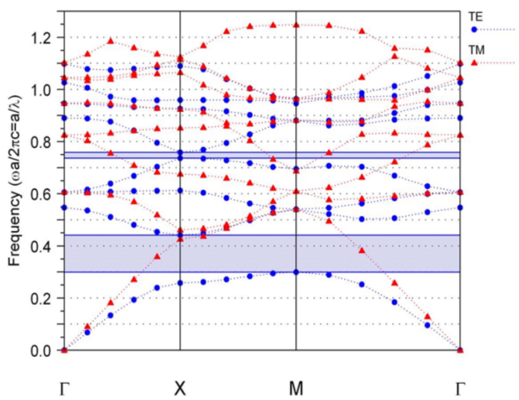



Fig. 1. Band diagram of 1×1 PC structure in square lattice.

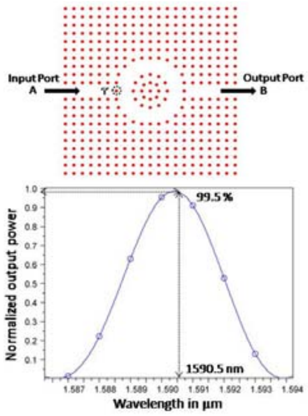
Figures 2(a) - 2(g) sketch the schematic structure with its characteristics of sensor based on circular PCRR with different number of coupling rods placed at input and output ports of the in-line quasi waveguides. The sensor consists of two inline quasi waveguides in horizontal (г-x) direction and a circular PCRR between them. The inline quasi waveguides are formed by introducing line defects and the circular PCRR is shaped by point defects. The line defects are carried out by removal or change of the row or column of rods in uniform direction whereas removal or change of one or more rods in non-uniform direction is point defects. The inner, center and outer rods are placed in the inline waveguides which are denoted by 'i', 'c', and 'o' respectively.

The circular PCRR is constructed by varying the position of inner rods and outer rods from its original position towards center of the origin. The inner rods and outer rods are built by varying the position of adjacent rods in the four sides, from its center, by 25% in both 'X' and 'Z' directions. The position of the rods is varied by varying the lattice constant [24].

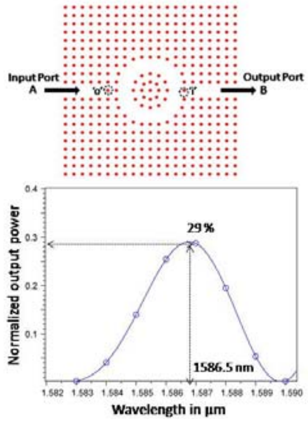
To identify the optimum number of coupling rods required to be kept in the in-line waveguides for designing the sensor, there are seven different cases considered. The resonant wavelength, Q factor and the output efficiency of those structures with different numbers of coupling rods are listed in Table 2. In Table 2, the resonant wavelength, output power (intensity) and Q factor of the sensor structure with one-one coupling rod are 1590.5 nm, 99.5% and 477.83, respectively, where one-one indicates that the number of coupling rods in the input side and output side is one, whereas two-one dictates that the numbers of coupling rods in the input side and output side are two and one, respectively. Similarly, two-one (with 2a) represents the number of coupling rods in the input side and output side are two and one, respectively, where '2a' represents the distance between the two input coupling rods from the cavity. It is seen that an increase in the number of coupling rods sufficiently reduces the output power at the resonant wavelength. The resonant wavelength, Q factor and the output power of the structures in Figs. 2 (a)-(g) are listed in Table 2 which is already reported [31]. As the structure with one-one offers substantial performance which has considered for analysing the sensing characteristics.

Table 2. The Resonant Wavelength, Output Power and Q Factor of the Structure Shown in Figs. 2 (a)-(g)

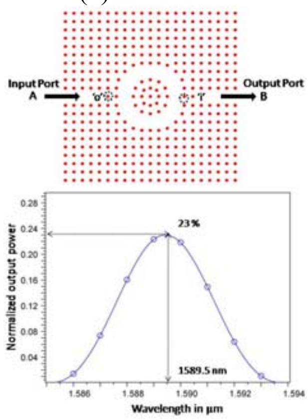
| Structures | Resonant Wavelength (nm) | Output Power (%) | Q Factor |
|---|---|---|---|
| One-One | 1590.55 | 99 | 477.64 |
| Two-One | 1586.5 | 29 | 466.66 |
| Two-One (with 2a) | 1589.0 | 5.2 | 496.56 |
| Two-Two | 1589.5 | 23 | 407.56 |
| Three-One | 1590.0 | 0.29 | 441.66 |
| Three-Two | 1586.0 | 0.081 | 422.93 |
| Three-Three | 1589.5 | 0.067 | 400.37 |



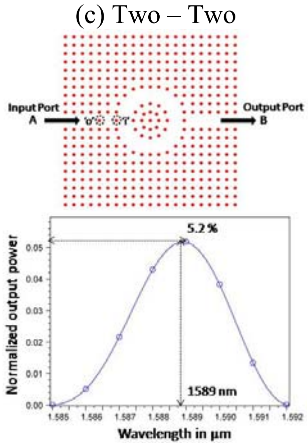

(a) One - One



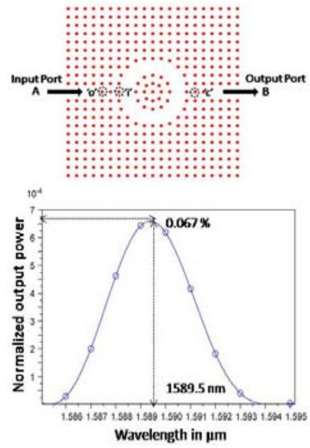

(b) Two - One



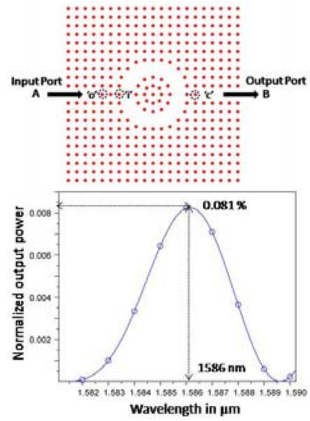

(c) Two – Two



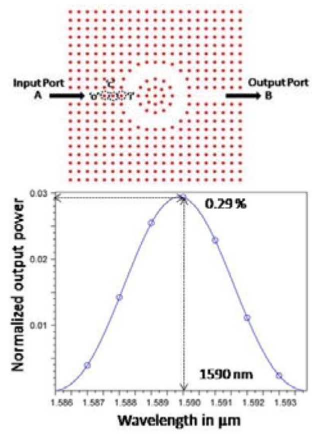

(d) Two - One (with 2a)




(e) Three - Three




(f) Three - Two




(g) Three – One

Fig. 2. Schematic structure and its characteristics of the structure with different coupling rods at input and output ports of the in-line quasi waveguides

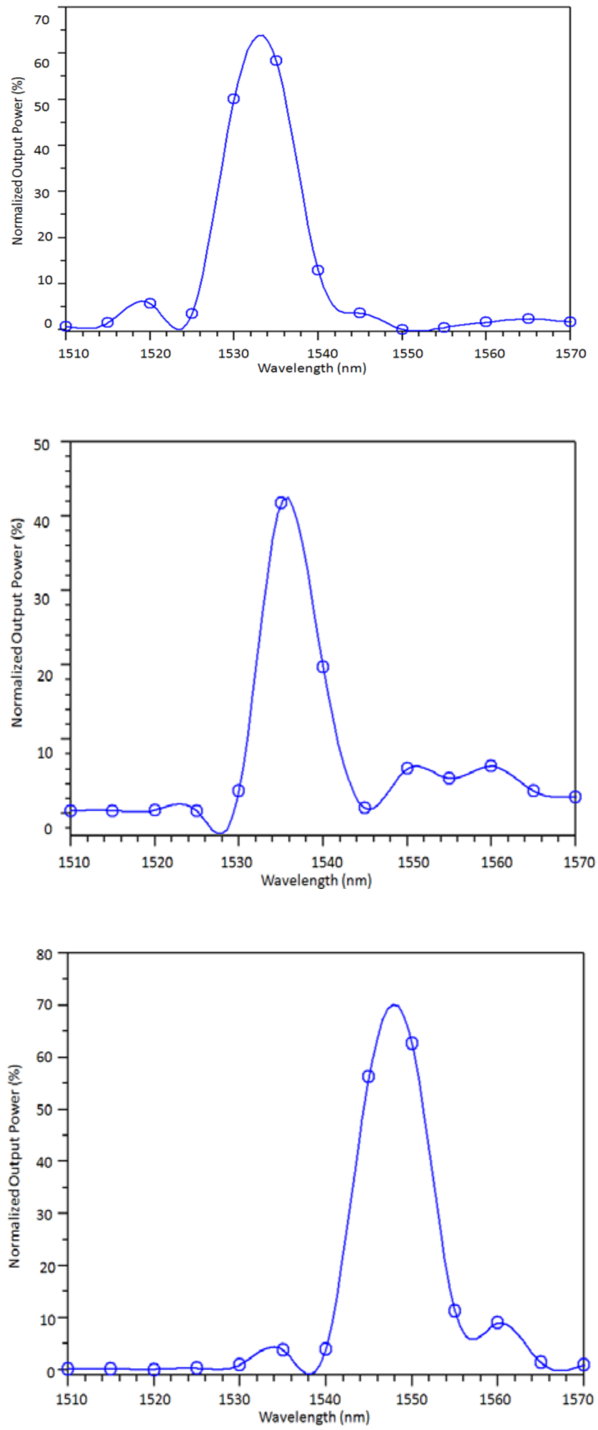
## III. ANALYSIS OF SENSING CHARACTERISTICS

The refractive index of the protein concentration increases linearly while increasing the level (Percentage) of protein concentration. In the PC structure, an increase in the refractive index, the resonant wavelength of the sensor is shifting to the higher wavelength and vice versa. It is noticed that the refractive index around 0.0110 is increased while increasing the protein concentration by 5 percentage (%). By combining the aforementioned principle, the sensing characteristics are analyzed. If the protein concentration is entered into the structure, the refractive index of the sensor varies according to the protein concentration, and the resonant wavelength of the sensor shifts to the higher wavelength region or lower wavelength region.

The Plane Wave Expansion (PWE) method is employed to estimate the band gap and propagation modes of PCs structure without and with defects. The 2D Finite-Difference Time-Domain (FDTD) method is used to investigate the performance of the sensor. A temporal light pulse is launched into the inline quasi waveguide. The output signal is recorded by a power monitor at the output port. The output spectrum is obtained by applying the Fast-Fourier Transform to the temporal signal recorded by the power monitor. The output signal power from the power monitor positioned at the output port is normalized by the input signal power.

Figs. 3 (a), (b) and (c) depict the normalized output spectra of the sensor (Figure 2(a)) at 0%, 50% and 100% of protein concentration, respectively. Here, variation of refractive index difference (delta) while changing the protein concentration is considered for analyzing the sensing possibility. The sensor is packaged in a fluidic channel, while analytes flow via the sensor the refractive index of the Si rods is changed. Owing to analytes, the refractive index of the sensor is varied which in turn the resonant wavelength is shifted.

It is clearly from the figure 3(a), 3(b) and 3(c), the resonant wavelenth of the sensor shifts to higher wavelength while incresing the protein concentration in the solution, as the increase in protein concentration resulting the increase in refractive index. The resonant wavelength, quality factor and output efficeincy of the senosr at 0% of protein concetration are 1532.5 nm, 153 and 65%, respectively. Similarly the resonant wavelength, quality factor and output efficeincy of the senosr at 50% and 100% of protein concetration are 1541.6 nm, 192 and 44%, and 1548 nm, and 1548.8 nm, 193.5, and 75%, respectively.




(c) 100% of Protein Concentration

Fig. 3. Normalized transmission spectra of sensor for protein concentration of (a) at 0% (b) 50% and (c) 100%

Table 3. Refractive Index, output power and Q facor of various protein concentration

| Protein Concent. | Ref. Index [24] | Resonant Wavelength (μm) | Output Power (%) | Q-Factor |
|---|---|---|---|---|
| 0% | 1.3400 | 1532.5 | 65 | 153.250 |
| 5% | 1.3510 | 1533.3 | 55 | 191.875 |
| 10% | 1.3621 | 1534.0 | 49 | 219.285 |
| 15% | 1.3731 | 1534.9 | 32.5 | 194.430 |
| 20% | 1.3842 | 1535.7 | 12 | 153.700 |
| 25% | 1.3952 | 1536.5 | 11.5 | 256.666 |
| 30% | 1.4063 | 1537.4 | 7.9 | 308.000 |
| 35% | 1.4173 | 1538.2 | 12.8 | 191.812 |
| 40% | 1.4284 | 1540.0 | 28 | 255.833 |
| 45% | 1.4394 | 1540.9 | 40 | 255833 |
| 50% | 1.4505 | 1541.6 | 44 | 192.000 |
| 55% | 1.4615 | 1542.4 | 48 | 170.888 |
| 60% | 1.4726 | 1543.1 | 68 | 213.888 |
| 65% | 1.4836 | 1544.0 | 85 | 197.435 |
| 70% | 1.4947 | 1544.7 | 85 | 192.500 |
| 75% | 1.5057 | 1545.4 | 78 | 154.200 |
| 80% | 1.5168 | 1546.0 | 86 | 171.555 |
| 85% | 1.5278 | 1546.7 | 98 | 220.642 |
| 90% | 1.5389 | 1547.3 | 96 | 220.714 |
| 95% | 1.5499 | 1548.0 | 85 | 171.544 |
| 100% | 1.5610 | 1548.8 | 75 | 193.500 |

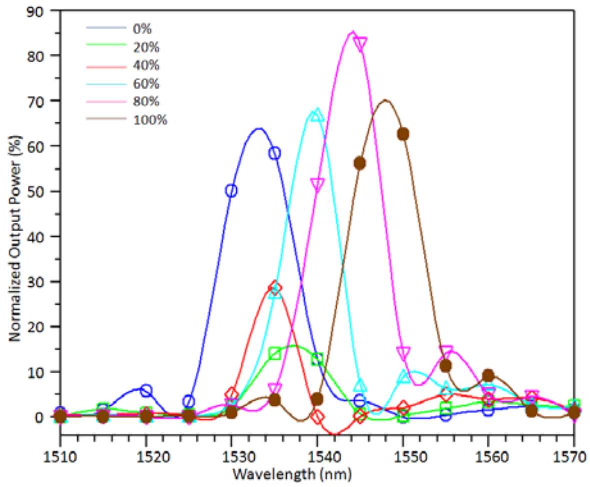



Fig. 4. Normalized output power of the protein sensor for protein concentration from 0% to 100%.

Fig. 4 depicts the effect of variation of normalized output power with respect to the protein concentration over the range of 0% to 100%. It is clearly noticed that the resonant wavelength of the sesnor shifts around 0.9 nm to higher wavelength when the level of protein concentration increases around 5% linearly. The percentage of protein concentration, corresponding refractive index, output efficiency and quality factor for the protein concentration of 0% to 100% are listed in Table 3. The sensitivity and dynamic range of the proposed sensor is 5% and 100%, respectively. The observed results with accounted values are highly sufficient for sensing the protein concentration. Hence, the proposed sensor is suitable for real time medical field applications.

## IV. Conclusion

In this paper, homogeneous, wavelength shift biosensor is proposed and designed for sensing the protein concentration using two-dimensional Photonic Crystal Ring Resonator (PCRR). It is observed that the resonant wavelength of the sensor is shifted to higher wavelength while increasing the protein concentration as the protein has a unique refractive index for each level. Around 1.5 nm wavelength shift is noticed to higher wavelength for every increasing 5% protein concentration. The size of the sensor is 11.4 μm × 11.4 μm, which is much smaller than the conventional one. The proposed sensor is very small size and operated at faster speed, hence, the proposed sensor could be implemented for medical field applications.

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## SCOPE

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