PHOTONIC SENSORS / Vol. 7, No. 1, 2017: 11–19

Photonic Crystal Based Biosensor for the Detection of Glucose Concentration in Urine

Savarimuthu ROBINSON* and Nagaraj DHANLAKSMI

Department of Electronics and Communication Engineering, Mount Zion College of Engineering and Technology, Pudukkottai, 622507, Tamil Nadu, India

*Corresponding Author: Savarimuthu ROBINSON E-mail: mail2robinson@gmail.com

Abstract: Photonic sensing technology is a new and accurate measurement technology for bio-sensing applications. In this paper, a two-dimensional photonic crystal ring resonator based sensor is proposed and designed to detect the glucose concentration in urine over the range of 0 gm/dl−15 gm/dl. The proposed sensor is consisted of two inverted "L" waveguides and a ring resonator. If the glucose concentration in urine is varied, the refractive index of the urine is varied, which in turn the output response of sensor will be varied. By having the aforementioned principle, the glucose concentration in urine, glucose concentration in blood, albumin, urea, and bilirubin concentration in urine are predicted. The size of the proposed sensor is about 11.4 μm×11.4 μm, and the sensor can predict the result very accurately without any delay, hence, this attempt could be implemented for medical applications.

Keywords: Biosensor; photonic crystal; refractive index; urine; glucose; urea

Citation: Savarimuthu ROBINSON and Nagaraj DHANLAKSMI, "Photonic Crystal Based Biosensor for the Detection of Glucose Concentration in Urine," *Photonic Sensors*, 2017, 7(1): 11–19.

1. Introduction

After the invention of the optical sensor by Clark and Lyons in 1962, optical sensing mechanisms receive considerable attention in the areas of industrial process control, military, environmental monitoring, medical diagnostics, etc. Glucose concentration is affected by the physical properties of refractive index, specific gravity, surface tension, and viscosity. Generally, glucose present in urine is referred as "Glycosuria" [2] and normal range from 0 mg/dl to 15 mg/dl. If the level is increased from the normal range, it means high glucose level in blood. Normal blood glucose level is between 165 mg/dl and 180 mg/dl. The level being too low is known as "Hypoglycemia", i.e. the range from less than 40 mg/dl. High blood glucose level is known as "Hyperglycemia" and ranges from 270 mg/dl to 360 mg/dl [2]. It indicates as diabetes mellitus, liver, and kidney related diseases [3–5].

According to the World Health Organization (WHO), about 422 million people are affected by diabetes in the year of 2014 [6]. The global prevalence of diabetes among adults over 18 years of age has risen from 4.7% in 1980 to 9% in 2015. Diabetes prevalence has been rising more rapidly in middle- and low-income countries. Diabetes is fast gaining the status of a potential epidemic in India with more than 62 million diabetic individuals currently diagnosed with the disease. In 2000, India (31.7 million) topped the world with the highest number of people with diabetes mellitus followed by

Received: 22 May 2016 / Revised: 5 September 2016

DOI: 10.1007/s13320-016-0347-3
Article type: Regular

China (20.8 million) and the United States (17.7 million) in the second and third place, respectively. The prevalence of diabetes is predicted to double globally from 171 million in 2000 to 366 million in 2030 with a maximum increase in India. It is predicted that by 2030 diabetes mellitus may afflict up to 79.4 million individuals in India. Also WHO noticed that diabetes is going to be the 7th leading diseases in the world, of which diseases are hardening of the arteries, heart disease, stroke, kidney disease, blindness, infections and loss of toes, feet, (or) fingers caused by poor circulation, and infection [7]. One-fifth of the world population is suffering from urine related problems [2].

The conventional prediction method monitors the glucose concentration in urine or blood. The pinpricking method is an invasive method for the analysis of glucose concentration in blood. However, it needs (5 mg/dl to 15 mg/dl) more blood samples [8]. Fluorescent glucose biosensor measures the concentration of glucose in diabetic patients and in small molecules dyes [9]. Continuous glucose monitoring method is used to measure the glucose concentration in blood by using the glucose sensor. The disposable sensor is placed under the skin which is very painful [8]. Another method is using test strips. In this method, the strip color is changed according to the concentration of glucose in urine. It is based on air borne or finger borne contamination. So, the result is inaccurate [10]. It is highly possible to get the accurate result with in the desired time using the photonic crystals (PC) based sensor.

In 1987, Yablonovitch introduced PC [11]. The photonic crystal is composed of periodic dielectric or metallo-dielectric nanostructures that have alternatively low and high dielectric constant materials (refractive index) to affect the propagation of electromagnetic waves inside the structure. PCs have a unique optical property called photonic band gap (PBG). Based on the variation of refractive index in one, two, and three directions, PCs are classified into three types namely one dimensional (1D), two dimensional (2D), and three dimensional (3D) PC. In this paper, we consider a 2DPC because it has a simple structure, small size, and high confinement of light and more convenient when compared with 1D and 3D photonic crystals. PC is providing an accurate sensing platform because of the strong confinement of light inside the device [12, 13]. Typically, PC is having PBG, which is entirely broken by introducing either line defect or point defect. By breaking the defects, PC based optical devices, such as filter [14, 15], directional coupler [16], demultiplexer [17, 18], triplexer [19, 20], power splitter [21, 22], logic gates [23], switches [24, 25], electro-optical modulators [26, 27], add-drop filter [28, 29], and sensors [30−41], were reported.

In the literature, PC/PCRR based sensors were reported for bio sensing applications [30, 31], salinity sensor for different temperatures [32], chemical sensor [33], force/strain sensor applications [34, 35], pressure sensor [36], biosensor to detect the glucose concentration in urine [5, 37, 38], aqueous environment [39], breast cancer [40], cancer cell detection [41], pregnancy test, etc. In this paper, a photonic crystal based biosensor is designed, and sensing characteristics such as the Q factor, resonant wavelength, and normalized output power are estimated for albumin, bilirubin, urea, and glucose in urine and also glucose concentration in blood. Rsoft FullWAVE and BandSOLVE simulator is employed to get band diagram and normalized output power of the sensor.

The reminder of the paper is given as follows. In Section 2, the sensing principle is discussed. The design of biosensor using 2DPC in square lattice is presented in Section 3. The obtained simulation results are discussed in 4 Section. Finally, Section 5 concludes the paper.

2. Biosensor design

The proposed PC based glucose sensor is used to detect the glucose, albumin, bilirubin, and urea concentration in urine and blood. The biosensor is

designed using 2DPC with circular rods in a square lattice. PCs control the flow of light inside the structure with the help of defects (point/line) which can be employed for sensing application [42, 43].

The 21×21 square lattice PC structure is considered for the biosensor design. The distance between the two nearest rods is 540 nm which is termed as a lattice constant, and it is denoted by "*a*". The radius of the rod is 100 nm. The refractive index of the Si rod is 3.46, and it is surrounded by air. The design parameter of the proposed sensor is listed in Table 1.

Table 1 Design parameters of the proposed biosensor.

Parameters	Values
Configuration	Rod in air
Rod shape	Circular
Lattice structure	Cubic/square
Lattice constant	0.540 μm
Radius of the rod	0.1 μm
Refractive index of the rod	3.46
Dielectric constant of Si rod	11.97

Figure 1(a) sketches the band diagram of the structure without any defects, which usually gives the range of transverse electric/transverse magnetic (TE/TM) PBG and propagation modes inside the periodic structure. There are two TM PBGs exist in the structure which are indicated by blue color. As TE PBG is not present in the structure, the TM polarization is considered for this simulation. The normalized frequency of the first reduced TM PBG is observed from 0.435 a/λ to 0.295 a/λ whose corresponding wavelength ranges from 1241 nm to 1830 nm, and the second PBG is from 0.754 a/λ to 0.732 a/λ whose corresponding wavelength spans from 716 nm to 737 nm. Out of these, the first reduced TM PBG is considered for designing biosensor as it covers the second and third windows in the optical region. When the defects are introduced in the structure, the PBG is broken, and the guided modes are allowed to propagate inside the PBG region as shown in Fig. 1(b). Both point and line defects are employed for designing the proposed sensor. The guided modes are regulated by controlling the defect size and shape.

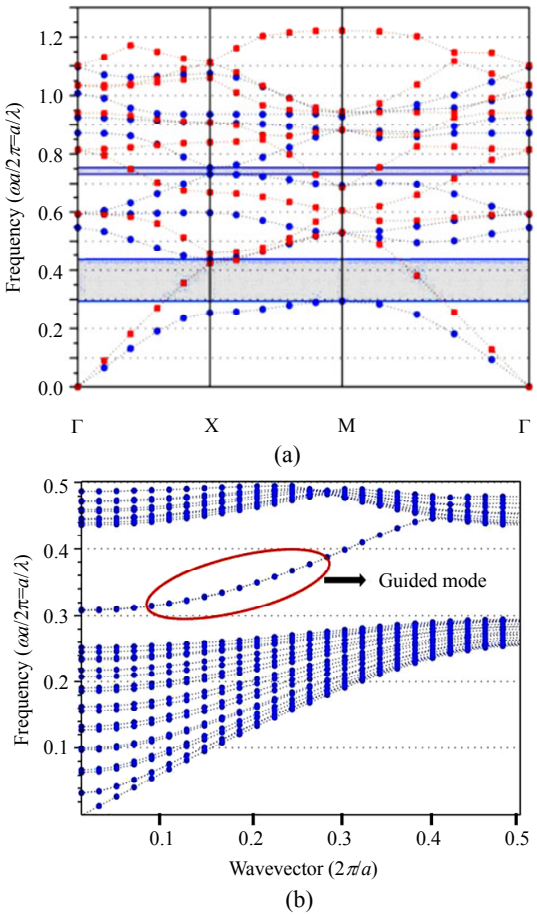


Fig. 1 Band diagram for circular rods in 21×21 square lattice: (a) without any defects and (b) with line and point defects.

The schematic representation of the proposed sensor is shown in Fig. 2. The proposed sensor is consisted of two inverted "L" waveguides and a ring resonator. The inverted "L" waveguide is created by introducing line defects, and the ring resonator is designed by having both line/point defects. Generally, to remove a row/column of rods is line defects whereas to remove or change structural parameters of a single rod is represented as point defects. The radius of the rod, lattice constant, and dielectric constant are the structural parameters. The circular ring resonator is shaped by altering original position of the rod [15]. The radii of the inner rod and outer rod are 50 nm and 100 nm, respectively. However, radius of the rod which is positioned top and bottom of the ring resonator is 86 nm in order to attain the higher output transmission. Figure 3 shows the 3D view of the proposed sensor which gives the overall size of the device is about 11.4 μm ×11.4 μm.

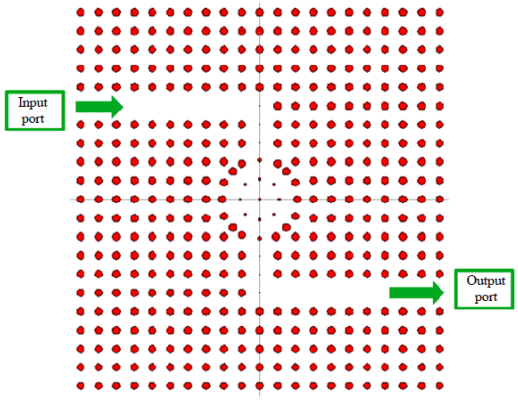


Fig. 2 Schematic structure of proposed photonic crystal based biosensor.

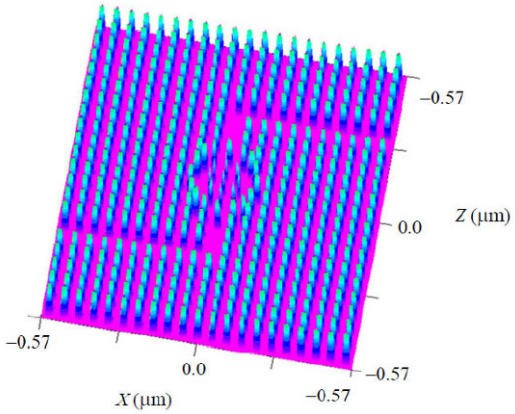


Fig. 3 3D view of the photonic crystal based biosensor.

3. Simulation results

The gaussian input is launched into the input port, and the output signal is obtained at the output port using power monitor. Typically, the signal is not reached to the ring resonator at OFF resonance condition. The signal from input "L" waveguide is coupled to the ring resonator and reached the output "L" waveguide through ring resonator at resonance. The normalized output spectra of proposed sensor are represented in Fig. 4. The resonant wavelength, output power, and Q factor of the proposed sensor are 1545 nm, 100%, and 257, respectively.

Figure 5 depicts the electric field distribution of the proposed sensor at ON resonance and OFF resonance. The input signal is reflected back to the input port at OFF resonance (1300 nm), however, at ON resonance (1545 nm), the input port signal is coupled from inverted "L" waveguide to ring resonator which in turn, outputs inverted "L" waveguide.

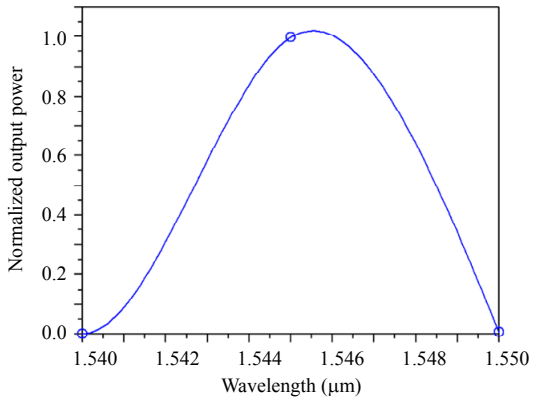
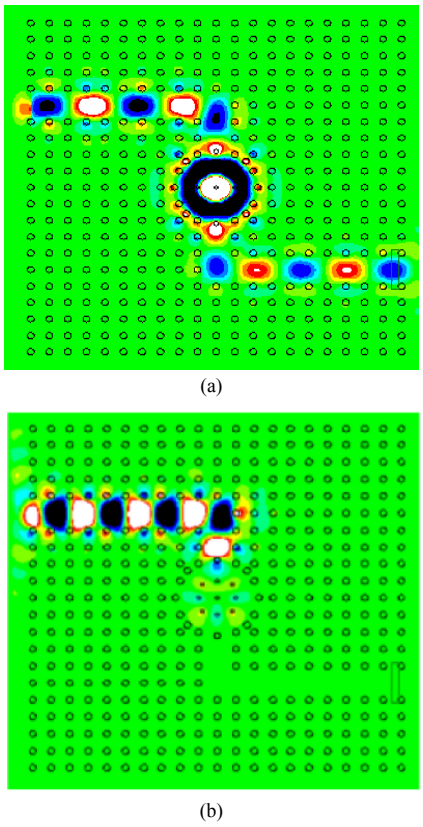


Fig. 4 Normalized transmission spectra of the proposed biosensor.



(a)

(b)

Fig. 5 Field distribution of the propose sensor at (a) ON resonance and (b) OFF resonance.

4. Results and discussion

The refractive index of the urine is varied, if the glucose concentration presented in the urine is varied. Generally, the effective refractive index of the structure is varied in the PC based sensor, either the output intensity will be varied or the resonant wavelength will be shifted from its original position. The intensity variation scheme is considered in this

work. The glucose concentrations in urine and its respective refractive indexes are listed in Table 2.

Table 2 Glucose concentration in urine and its refractive index, resonant wavelength, normalized output power, and *Q* factor of the proposed sensor.

Glucose concentration in urine	Refractive index [2]	Resonant wavelength (nm)	Normalized output power	*Q* factor
Normal (0 mg/dl - 15 mg/dl)	1.335±0.001	1 585	1	264
0.625 gm/dl	1.336±0.001	1 585	0.96	269
1.25 gm/dl	1.337±0.001	1 585	0.92	260
2.5 gm/dl	1.338±0.001	1 585	0.85	252
5 gm/dl	1.341±0.001	1 585	0.55	217

Figure 6 depicts the normalized output spectra of the proposed sensor for glucose concentration in urine ranging from 0.625 gm/dl to 5 gm/dl. It is investigated that the output power is decreased while increasing the glucose concentration in urine. If the glucose concentration in urine is increased, the refractive index of the urine is increased; however, in a PC based sensor, the output power is reduced. The proposed sensor is followed the intensity reduction while increasing the refractive index. The resonant wavelength, *Q* factor, and normalized output power of the sensor for glucose concentration in urine over the range from 0.625 gm/dl to 5 gm/dl/, are reported in Table 2. The output spectra for different glucose concentrations in urine are depicted in Fig. 7. At the normal condition, the resonant wavelength, output power, and *Q* factor of the sensor for predicting the glucose concentration are 1545 nm, 100%, and 256, respectively.

Figure 8 shows the normalized output spectra of the sensor for different glucose concentrations in blood. It is observed that the refractive index of the blood is increased while increasing glucose concentration presented in the blood. The output intensity is decreased for every increasing glucose concentration in urine. The normalized output power is decreased if the refractive index of the concentration is increased. The cumulative dielectric strength of sensor is improved linearly while increasing refractive index of the concentration, hence, the intensity of the sensor is minimized. The refractive index, resonant wavelength, *Q* factor, and normalized output power of the sensor for different values of glucose concentration in blood are reported in Table 3.

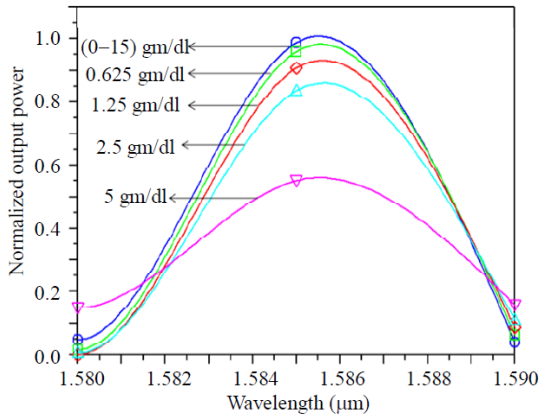


Fig. 6 Normalized output power for different glucose concentrations in urine.

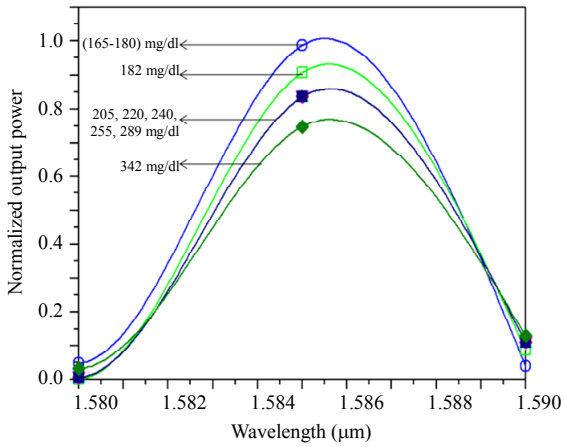


Fig. 7 Normalized output power for different glucose concentrations in urine.

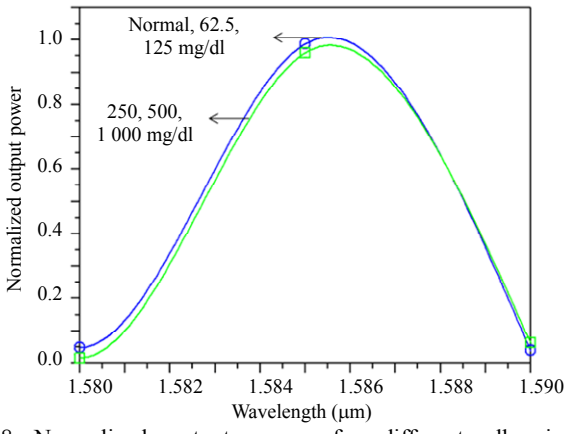


Fig. 8 Normalized output power for different albumin concentrations in urine.

Table 3 Glucose concentration in blood and its refractive index, resonant wavelength, normalized output power, and Q factor of the proposed sensor.

Glucose concentration in blood	Refractive index [2]	Resonant wavelength (nm)	Normalized output power	Q factor
Normal (165 mg/dl − 180 mg/dl)	1.335	1 585	1	264
182 mg/dl	1.337	1 585	0.9	260
205 mg/dl - 289 mg/dl	1.338	1 585	0.83	252
342 mg/dl	1.339	1 585	0.75	269

Generally, four different components, namely glucose, albumin, urea, and bilirubin, are presented in urine. It is highly essential to maintain the aforementioned concentration as its desired level. Otherwise, the health will be affected. The health issues while varying the glucose, albumin, urea, and bilirubin concentration from the normal value are listed in Table 4.

Table 4 Health issues for different glucose, albumin, urea, and bilirubin concentrations present in urine.

Samples	Normal range	Refractive index	Health issues
Glucose	0 gm/dl− 15 gm/dl	1.335 ± 0.001	> Diabetes < No issues
Albumin	4 gm/dl− 6 gm/dl	1.335 ± 0.002	> Kidney diseases < Liver diseases like hepatitis
Urea	60 gm/dl− 100 gm/dl	1.335 ± 0.001	> Decrease blood flow of the kidney, heart diseases < Kidney diseases
Bilirubin	< 1 gm/dl	1.335 ± 0.001	> Jaundice, liver cancer < No issues

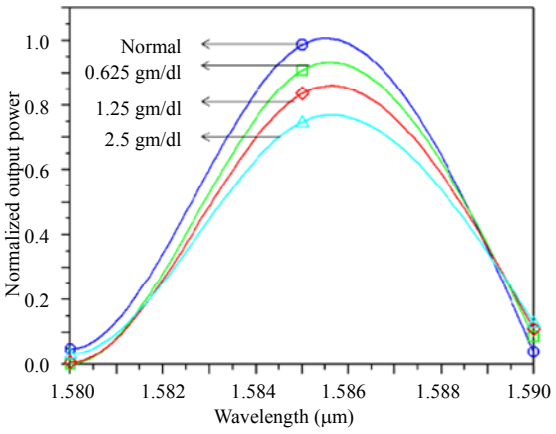


Fig. 9 Normalized output power for different urea concentrations in urine.

The normalized output spectra of the proposed sensor for different values of albumin, urea, and bilirubin present in urine are shown in Figs. 8, 9, and 10, respectively. The concentrations of albumin, urea, and bilirubin with corresponding refractive index, resonant wavelength, normalized output power, and Q factor are listed in Tables 5, 6, and 7, respectively.

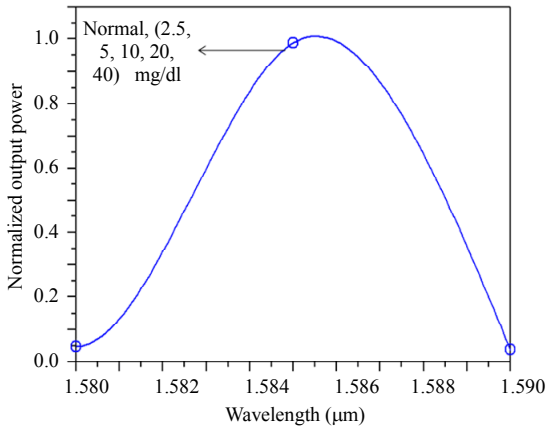


Fig. 10 Normalized output power for different bilirubin concentrations in urine.

Table 5 Albumin concentration in urine and its refractive index, resonant wavelength, normalized output power, and Q factor of the proposed sensor.

Albumin concentration in urine	Refractive index [2]	Resonant wavelength (nm)	Normalized output power	Q factor
7 mg/dl − 125 mg/dl	1.335±0.002	1585	1	264
250 mg/dl− 1000 mg/dl	1.336±0.002	1585	0.95	269

Table 6 Urea concentration in urine and its refractive index, resonant wavelength, normalized output power, and Q factor of the proposed sensor.

Urea concentration in urine	Refractive index [2]	Resonant wavelength (nm)	Normalized output power	Q factor
Normal (60 gm/dl − 100 gm/dl)	1.335±0.001	1 585	1	264
0.625 gm/dl	1.337±0.002	1 585	0.98	260
1.25 gm/dl	1.338±0.002	1 585	0.85	252
2.5 gm/dl	1.339±0.001	1 585	0.75	269

Table 7 Bilirubin concentration in urine and its refractive index, resonant wavelength, normalized output power, and Q factor of the proposed sensor.

Bilirubin concentration in urine	Refractive index [2]	Resonant wavelength (nm)	Normalized output power	Q factor
Normal - 40 mg/dl	1.335±0.001	1585	1	264

From the aforementioned simulation results, it is

investigated that if the concentration of glucose, albumin, urea, and bilirubin present in the urine is increased, then the respective refractive index is increased, and in turn output power of sensor is decreased. By knowing the output power of the sensor, the respective concentration will be measured. The ultra-compact proposed sensor is designed using 2DPC which requires very smaller amount of samples to detect the concern parameters. In addition, the proposed sensor will respond very quickly, and the size is very small about 11.4 μm×11.4 μm. Hence, the proposed sensor will be employed for bio sensing applications.

5. Conclusions

The two dimensional photonic crystal based biosensor is designed for detecting glucose concentration in urine, and its sensing characteristics are analyzed. The sensor is designed using two dimensional photonic crystals with the cubic lattice of circular rod surrounded by air. The proposed sensor is designed to operate over the wavelength range between 1540 nm and 1550 nm. The sensor is used to predict urea, albumin, bilirubin, and glucose concentration in urine and glucose concentration in blood. The size of the propose sensor is 11.4 μm×11.4 μm. The proposed sensor performs better than the reported conventional sensor for predicting the glucose concentration in urine, hence, this sensor will be incorporated for medical applications.

References

[1] L. C. Clark and C. Lyons, “Electrode systems for continuous monitoring in cardiovascular surgery,” *Annals of the New York Academy of Sciences*, 1962, 102(1): 29–45.

[2] S. I. Ahmad, “Studies on some biophysical aspects of human renal excretory fluid,” Ph.D. dissertation, Department of Physics, Jawaharlal Nehru Technological University, Hyderabad, India, 2010.

[3] P. Sharma, S. K. Roy, and P. Sharan, “Design and simulation of photonic crystal based biosensor for detection of different blood components,” in *Proceeding of IEEE Region 10 Symposium*, Kulala Lumpur, Malaysia, pp. 171–176, 2014.

[4] P. Sharma, P. Deshmukh, and P. Sharan, “Design and analysis of blood components by using optical sensor,” *International Journal on Current Research*, 2013, 5(8): 2225–2228.

[5] P. Sharma and P Sharan, “Photonic crystal based sensor for detection of high glucose concentration in urine,” in *Proceeding of Annual IEEE India Conference*, vol. 19, pp. 184–191, 2015.

[6] World Health Organization, *Fact Sheet N312*, Available online: http://www.who.int.int/mediacentre/factsheets/fs312/en/, 2014.

[7] Agency for Healthcare Research and Quality, Available online: http://www.Ahrq.gov, 2012.

[8] Blood Glucose Monitoring-Wikipedia, *The Free Encyclopedia*, Available online: http://en.wikipedia.org/wiki/Blood_glucose_monitoring, 2014.

[9] Fluorescent Glucose Biosensor the Free Encyclopedia, Available online: http://en.wikipedia.org/wiki/Fluorescent_glucose_monitoring, 2015.

[10] Diabetes Care-Blood Glucose Test Strips, Available online: http://www.diabetes_cara/diabetes-test-strips.html, 2014.

[11] E. Yablonovitch, “Inhibited spontaneous emission in solid-state physics and electronics,” *Physical Review Letters*, 1987, 58(20): 2059–2062.

[12] M. R. Lee and P. M. Fauchet, “Two-dimensional silicon photonic crystal based biosensor platform for protein detection,” *Optics Express*, 2007, 15(8): 4530–4535.

[13] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic crystal: modeling of flow of light*. Princeton: Princeton University Press, 1995.

[14] S. Robinson and R. Nakkeeran, “Investigation on two dimensional photonic crystal resonant cavity based band pass filter,” *Optik-International Journal for Light and Electrons Optics*, 2012, 123(5): 451–457.

[15] L. Li and G. Q. Liu, “Photonic crystal ring resonator channel drop filter,” *Optik-International Journal for Light and Electrons Optics*, 2013, 124(17): 2966–2968.

[16] B. J. Luff, R. D. Harris, J. S. Wilkinson, R. Wilson, and D. J. Schiffrin, "Integrated-optical directional couplerbiosensor," *Optics Letters*, 1996, 21(8): 618–620.
[17] T. Saranya, S. Robinson, and K. V. Shanthi, "Design and simulation of two dimensional photonic crystal ring resonator based four port wavelength demultiplexer," *International Journal of Innovative, Science, Engineering and Technology*, 2013, 1(2): 154–161.
[18] M. R. Rakhshani and M. A. Mansouri-Birjandi, "Wavelength demultiplexer using heterostructure ring resonators in triangular photonic crystal," *Telkomnika Indonesian Journal of Electrical Engineering*, 2013, 11(4): 1721–1724.
[19] M. R. Rakhshani and M. A. Mansouri-Birjandi, "Design and optimization of photonic crystal triplexer for optical networks," *International Journal of Computer Science Issues*, 2012, 9(4): 24–28.
[20] A. Labbani and B. Abdelmadjid, "Design of photonic crystal triplexer with core-shell rod defects," *Chinese Physics Letters*, 2015, 32(5): 63–65.
[21] J. H. Chen, Y. T. Huang, Y. L. Yang, and M. F. Lu, "Design, fabrication and characterization of Si-based ARROW photonic crystal bend waveguides and power splitters," *Journal of Applied Optics*, 2012, 51(24): 5876–5884.
[22] M. M. Khan, "Nano structure based power splitter design by using 2D photonic crystals," *Journal of Modern Science and Technology*, 2013, 1(1): 176–187.
[23] R. Bchir, A. Bardaoui, and H. Ezzaouia, "Design of silicon-based two-dimensional photonic integrated circuits: XOR gate," *Journal of IET Optoelectronics*, 2013, 7(1): 25–29.
[24] K. Fasihi, "High-contrast all-optical controllable switching and routing in nonlinear photonic crystals," *Journal of Lightwave Technology*, 2014, 32(18): 3126–3131.
[25] K. Cui, Q. Zhao, X. Feng, Y. Huang, Y. Li, D. Wang, *et al*., "Thermo-optic switch based on transmission-dip shifting in a double-slot photonic crystal waveguide," *Applied Physics Letters*, 2012, 100(20): 1–4.
[26] J. M. Brosi, C. Koos, L. C. Andreani, M. Waldow, J. Leuthold, and W. Freude, "High-speed low-voltage electro-optic modulator with a polymer-infiltrated silicon photonic crystal waveguide," *Optics Express*, 2008, 16(6): 4177–4191.
[27] Y. Gao, R. J. Shiue, X. Gan, L. Li, P. Cheng, I. Meric, *et al*., "High-speed electro-optic modulator integrated with graphene-boron nitride heterostructure and photonic crystal nanocavity," *Nano Letters*, 2015, 15(3): 2001–2005
[28] S. Robinson and R. Nakkeeran, "Photonic crystal ring resonator based add-drop filter for CWDM systems," *Optik-International Journal for Light and Electrons Optics*, 2013, 124(3): 3430–3435.
[29] H. Alipour-Banaei, F. Mehdizadeh, and M. Hassangholizadeh-Kashtiban, "A new proposal for PCRR-based channel drop filter using elliptical rings," *Physica E: Low-Dimensional Systems and Nanostructures*, 2014, 56(2): 211–215.
[30] P. Sharma, "Photonic crystal based ring resonator sensor for detection of glucose concentration for biomedical application," *International Journal of Emerging Technology and Advanced Engineering*, 2014, 4(3): 702–706.
[31] S. Olyaee and A. M. Bahabady, "Designing a novel photonic crystal nano-ring resonator for biosensor application," *Optical and Quantum Electronics*, 2014, 53(6): 1881–1888.
[32] S. Robinson and R. Nakkeeran, "PC based optical salinity sensor for different temperatures," *Photonic Sensors*, 2012, 2(2): 187–192.
[33] F. L. Hsiao and C. Lee, "Computational study of photonic crystal nano-ring resonator for biomedical sensing," *IEEE Sensors Journal*, 2010, 10(7): 1185–1191.
[34] R. M. Silva, M. S. Ferreira, J. L. Santos, and O. Frazao, "Nanostrain measurement using chirped Bragg grating Fabry-Perot interferometer," *Photonic Sensors*, 2012, 2(1): 77–80.
[35] T. T. Mai, F. L. Hsiao, C. Lee, W. F. Xiang, C. C. Chen, and W. K. Choi, "Optimization and comparison of photonic crystal resonators for silicon microcantilever sensors," *Sensors and Actuators A Physical*, 2011, 165(1): 16–25.
[36] K. Vijayashanthi and S. Robinson, "Two-dimensional photonic crystal based sensor for pressure sensing," *Photonic Sensors*, 2014, 4(3): 248–253.
[37] P. Sharma and P. Sharan, "Design of photonic crystal based biosensor for detection of glucose concentration in urine," *IEEE Sensors Journal*, 2015, 15(2): 1035–1042.
[38] P. Sharma and P. Sharan, "An analysis and design of photonic crystal based biochip for detection of glycosuria," *IEEE Sensor Journal*, 2015, 15(10): 5569–5575.
[39] F. Abdalmalek, "Design of a novel left-handed photonic crystal sensor operating in aqueous environment," *IEEE Photonic Sensors*, 2011, 23(3): 188–190.

[40] F. D. Gudagunti, P. Sharma, S. Talabattula, and V. Nainitej, "Early stage detection of breast cancer using hybrid photonic crystal ring resonator," in *Proceeding of IEEE International Conference on Advanced Communication Control and Computing Technologies*, Ramanathapuram, pp. 1–4, 2014.

[41] P. Sharan, S. M. Bharadwaj, F. D. Gudagunti, and P. Deshmukh, "Design and modeling of photonic sensor for cancer cell detection," *International Conference on the Impact of E-Technology on US*, 2014, 40(14): 20–25.

[42] R. D. Meade, A. M. Rappe, K. D. Brommer, and J. D. Joannopoulos, "Existence of a photonic band gap in two dimensional," *Applied Physics Letters*, 1992, 61(4): 495–497.

[43] J. D. Joannopoulos, P. R. Villeneuve, and S. Fan, "Photonic crystals: putting a new twist on light," *Nature*, 1997, 386(6621): 143–149.