

Modelling and Analysis of Photonic Sensor Based on Ring Resonator for Glucose Detection

Ambika. S^{#1}, Kalpana Vanjerkhede^{*2}

[#]Electronics and Communication Engineering, BTI College of Engineering, Bangalore

^{*}Electronics and Instrumentation Engineering, P. D. A College of Engineering, Kaburgi

Abstract – Diabetes is today's major global problem. Continuous monitoring of blood/urine glucose level is prerequisite for diabetic patient. In the proposed work we consider the two-dimensional photonic crystal-based biosensor for detecting glucose level in human body. Two ring resonator structure such as horizontal loop double ring resonator and vertical loop double ring resonator is considered. Wavelength shift is obtained for identification of glucose level in blood and urine. Quality factor, sensitivity and transmission efficiency of designed sensor is investigated. Maximum quality factor 12343 is obtained for horizontal loop double ring resonator structure compared to vertical loop double ring resonator structure. Sensitivity of 5681nm/RIU is obtained for horizontal loop ring resonator structure. Maximum wavelength range is obtained for horizontal loop double ring resonator structure. Result obtained shows promising for future fabrication feasibility.

Keywords: Ring resonator, Photonic Crystal, Glucose, Blood, Urine, Vertical Loop, Horizontal Loop.

I. INTRODUCTION

According to the American association data, 8.3% of total population, i.e around 25.8 billion population are suffering from the diabetes in each year. The different technologies are used in glucose detection. Glucose concentration is affected by different critical parameters such as refractive index, surface tension and viscosity. Glucose in the urine condition is called glycosuria. Normal range of glucose in human is 0mg/dl to 15mg/dl. If the glucose level is increased above this range it is considered as hyperglycemia and if the glucose level is decreased below this range it is considered as hypoglycemia. But continuous and regular interval glucose monitoring is necessary for optimal diabetic management. Monitoring the glucose concentration by using invasive and noninvasive method involves responses with analytical solution. Major advancement has been taken place in the case of self-monitoring of the blood glucose or abetted mentoring of the blood glucose in current era [1]. Different techniques have been considered in glucose monitoring. i) Non-Invasive optical glucose monitoring ii) Noninvasive fluid sampling glucose monitoring and iii) Minimal invasive glucose monitor. These techniques provide continuous glucose monitoring in blood or urine with no pain or slight pain. Invasive glucose monitoring involves the process of collecting blood sample by breaking skin barrier of patient's finger by sharp blood pricking device [2]. Beginning of optical techniques involved following methods, such as optical transmission spectroscopy, diffuse reflectance spectroscopy, optical coherence tomography, photoacoustic spectroscopy etc. Photonic crystal based multichannel nanocavity sensor has been designed and analyzed for detecting glucose monitoring. Designed sensor allowed operating range of

wavelength between 1300nm to 1700nm [3]. Optical monitoring of noninvasive based glucose monitoring sensor has been designed and fabricated. Experiment has been constituted the sensor output power and glucose concentration. But NIR spectroscopy has great potential in monitoring blood glucose. Similarly photonic crystal based two inverted L waveguide and ring resonator structures has been discussed. In this sensing structure urine-based samples are considered for monitoring glucose concentration in diabetic patients [4]. Photonic crystal fibre based plasmonic sensor has been developed for detection of glucose. Amplitude sensitivity of 152nm/RIU and maximum sensitivity of 2500nm/RIU is obtained for proposed sensor [5]. Point of care photonic crystal-based sensor has been designed for different applications. Flexible and wearable sensor has been designed and analyzed in the proposed structure [6][7]. Optical surface wave considered for biosensing applications. Angular interrogation with optical surface wave is utilized for investigation of photonic crystal sensing layer. Graphene coated photonic crystal-based sensing layer has been demonstrated with surface plasmon resonance. Sensor is investigated with aqueous solution. Average wavelength sensitivity of 2000nm/RIU is obtained during the analysis [8]. Biophotonic based sensor has been designed for brain lesions using one dimensional photonic crystal. Figure of merit 6.1×10^7 (RIU) achieved. Dissimilar brain lesion cells such as wall of solid brain, multiple sclerosis, oligodendroglioma, gray matter, white matter, glioblastoma, lymphoma, metastasis is considered for sensing analysis [9]. Photonic structures are optical nano structure that affect the movement of light in great comparable to how ionic lattices affect the electrons motions in solids. Propagation of light wave gets affected due to presence of different bio medium in the sensing structure. Overall refractive index of sensing structure changes i.e. effective refractive index changes.

Numerous works has been carried out with different sensing structures of photonic crystal for bio sensing applications. But proposed work focused on design of two different photonic sensing structures for monitoring human glucose level by invasive and noninvasive method. By considering integrated photonic ring resonator sensor based horizontal and vertical loop sensing structure two different types of sensing system can be fabricated for different applications. Successful design and simulation of these structures for glucose sensing application are feasible for future fabrication by achieving high Q factor and high sensitivity. During the propagation of light wave in the bio sample, propagation velocity of electromagnetic wave changes due to change in refractive index of bio sample.

In the photonic crystal, light wave propagation is obtained by Maxwell equation (1).

$$\nabla \times \left(\frac{1}{\epsilon} \nabla \times H \right) = \left(\frac{\omega}{c} \right)^2 H \quad (1)$$

In the above equation ‘H’ is the magnetic field and ‘c’ is velocity of light. ‘ ϵ ’ is permittivity (dielectric function) and is equal to η^2 . Where η is refractive index. ω is frequency, where ω is inversely proportional to dielectric function ϵ .

II. DESIGN AND WORKING PRINCIPLE

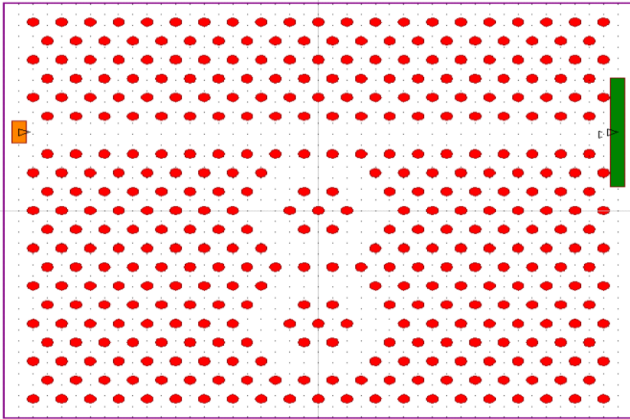


Figure 1: Vertical loop double ring resonator

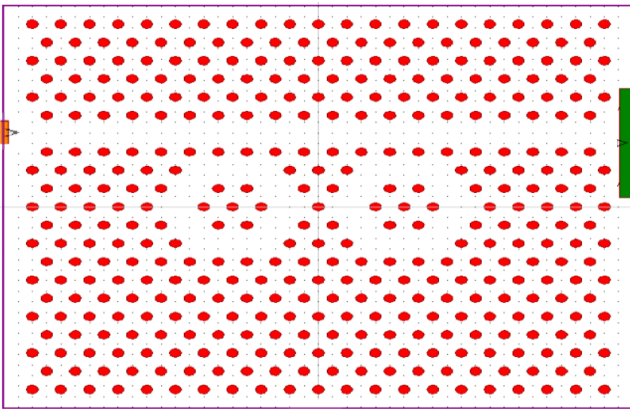


Figure 2: Horizontal loop double ring resonator

In this work, photonic sensing layer design consist of two approaches. Horizontal loop double ring resonator and vertical loop double ring resonator structure. This sensing resonator structure is designed with lattice constant of $1\mu\text{m}$. Radius of micro pillar is $0.17\mu\text{m}$. Two hexagonal ring structures are designed in vertical loop and horizontal loop for choosing the better sensing structure for glucose monitoring with the invasive and noninvasive techniques. Proposed biosensor has provided excellent quality factor with inducing vertical and horizontal loop ring resonator structure. A photo detector is placed at the end of ring resonator structure and Gaussian light source enters the ring resonator waveguide structure. Thickness of perfectly matching layer considered is $1\mu\text{m}$. Design and simulation of sensing structure is carried out in RSoft full wave module. Required design parameters are incorporated in Rsoft CAD environment as per the requirement in each stage of design. TE photonic bandgap in the range of 1327nm to 1656nm is obtained. At these regions of wavelength propagation of TE mode is strictly prohibited. This photonic bandgap acts as optical insulator allowing only specific range of wavelength.

Two-dimensional finite difference time domain and plane wave expansion is used for analyzing band gap of the proposed sensor. Sensor is incorporated with micro fluidic channels; this will be utilized for introducing the bio sample. Light propagation in the photonic crystal will vary with change in refractive index of bio sample considered during the analysis. Total dimension of the sensing structure is $28\mu\text{m} \times 28\mu\text{m}$. Table I shows the basic design parameters of sensing structure.

The refractive index of bio sample is used on the waveguide created in the photonic sensing structure. Photonic sensing layer is periodic arrangement of silicon based micro pillar structures. Two-dimensional photonic crystal designed here are periodic in two directions. Periodicity in the arrangement of micro pillars in the sensing structures causes bandgap. Design of the sensing structure is optimized with below parameters in multiple times to get the good quality factor and sensitivity.

Table I: Design parameters of sensing structures

Radius of micro pillar	$0.17\mu\text{m}$
Lattice constant	$1\mu\text{m}$
Wavelength of light	1550nm
Lattice configuration	Hexagonal
Micro Pillar Dielectric Constant	12
Sensor total dimension	$28\mu\text{m} \times 28\mu\text{m}$.

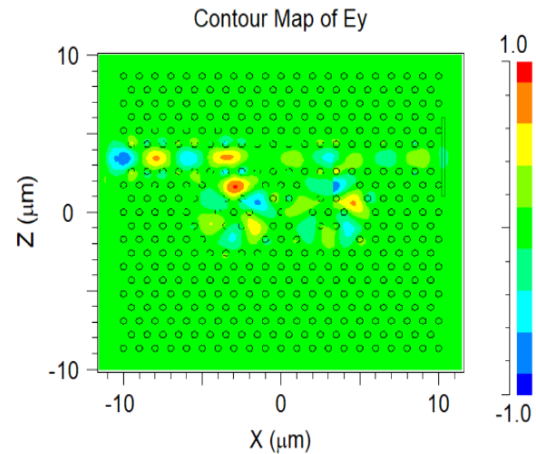


Figure 3: Light propagation in horizontal loop double ring resonator

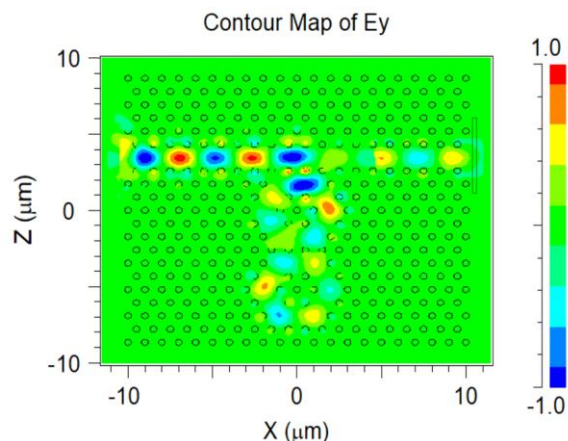


Figure 4: Light propagation in vertical loop double ring resonator

III. RESULTS AND DISCUSSION

Gaussian light source is launched from the input port. Power monitor is used to get the output signals. As the intensity of light propagation reduces, there will be reduction in the amount of light waves reaching the output. The signal from the input port propagates through the photonic waveguides and generates the constructive interference with the ring resonator to upgrade the light intensity to strengthen the output signals. Signal from the input port is coupled with vertical loop ring resonators and horizontal loop ring resonators and reaches the output port due to resonance generated in the resonator. Figure 1 and Figure 2 shows the double ring resonator structure designed in the Rsoft tool. Figure 3 and Figure 4 shows the light wave propagation in two types of resonators and its distribution in the sensing structure. Dark blue and red indicates electromagnetic light propagation in waveguide structure with high and low point such as crest and trough respectively. Briefly, it makes the color scale to go from dark blue (negative) to white (zero) to dark red (positive) for electromagnetic field value distribution.

Refractive index of urine and blood changes with change in concentration of glucose presence in blood and urine. Effective refractive index of sensing structure changes with change in overall refractive index. There will be change in intensity and shift in wavelength for overall refractive index change. In this work, shift in wavelength scheme is considered. The glucose concentration in blood are mentioned in Table II and Table III. Glucose concentration in urine are mentioned in Table IV and Table V. Glucose concentration in urine ranges from 0 to 5gm/dl. There is shift in wavelength for each change in glucose concentration in urine. Range of wavelength obtained for horizontal loop double ring resonator and vertical loop double ring resonators are evaluated.

Table II: Blood glucose concentration and transmission spectrum data - Horizontal loop double ring resonator

Glucose concentration in blood	Refractive Index	Resonant wave length	Transmission efficiency	Q Factor
Normal (0mg/dl)	1.30	1235.5	98	8323
50mg/dl	1.32	1236	98	8243
100mg/dl	1.34	1236.8	98	8535
150mg/dl	1.36	1237	98	8345

Table III: Blood glucose concentration and transmission spectrum data - Vertical loop double ring resonator

Glucose concentration in blood	Refractive Index	Resonant wave length	Transmission efficiency	Q Factor
Normal (0mg/dl)	1.30	1096	95	845
50mg/dl	1.32	1096.2	95	862
100mg/dl	1.34	1096.6	95	865
150mg/dl	1.36	1097	95	854

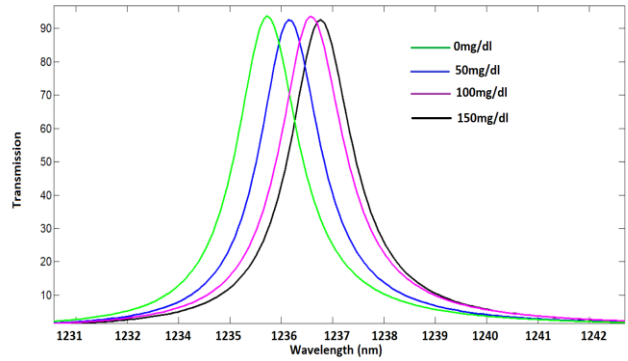


Figure 5: Blood glucose concentration analysis with horizontal loop double ring resonator

Proposed sensor with hexagonal lattice structure is shown in Figure 1 and Figure 2. TE band gap range between 900nm to 1400nm obtained for horizontal loop double ring resonator structure and is shown in Figure 7. For vertical loop double ring resonator 1080nm to 1400nm bandgap range obtained and is shown in the Figure 8. Photonic bandgap varies with varying the photonic sensing structure. Optimizing the photonic sensing structure to get the suitable sensitivity and operating wavelength range between 850nm to 1600nm is primary functional things involved in bandgap analysis. Proposed sensing structure has shown feasible operating wavelength which can incorporated for sensing bio sample. Glucose in blood varies with concentration from 0 – 150mg/dl. For this change of glucose concentration in blood, wavelength shifted from 1235.5nm to 1237nm for horizontal loop double ring resonator. And shift in wavelength observed for vertical loop double ring resonator was 1096nm to 1097nm as shown in Table II and Table III.

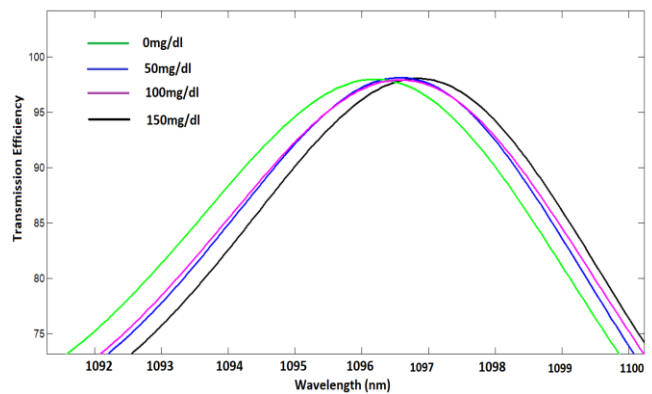


Figure 6: Blood glucose concentration analysis with vertical loop double ring resonator

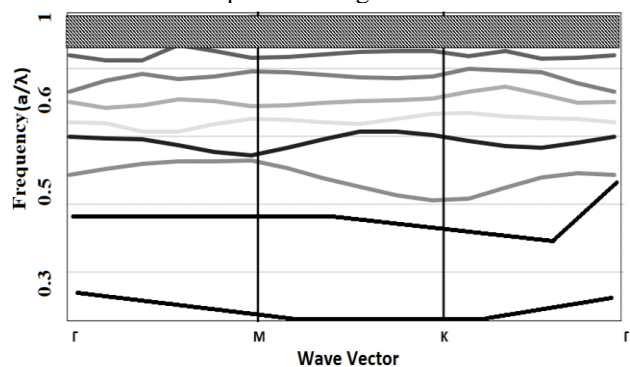


Figure 7: Bandgap analysis for horizontal loop double ring resonator

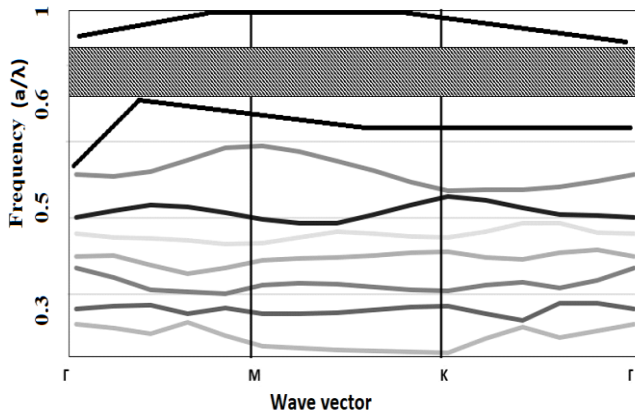


Figure 8: Bandgap analysis for vertical loop double ring resonator

It is investigated from the result that in case of glucose concentration in urine range of wavelength shift obtained for horizontal loop double ring resonator is 1333.5nm to 1396nm and for vertical loop double ring resonator ranges from 1383nm to 1396nm as shown in Table IV and Table V. As the concentration of urine increases, refractive index increases. Sensor total dielectric strength increases linearly with increase in refractive index. Figure 9 and Figure 10 shows the transmission spectrum for sensing analysis for urine glucose detection.

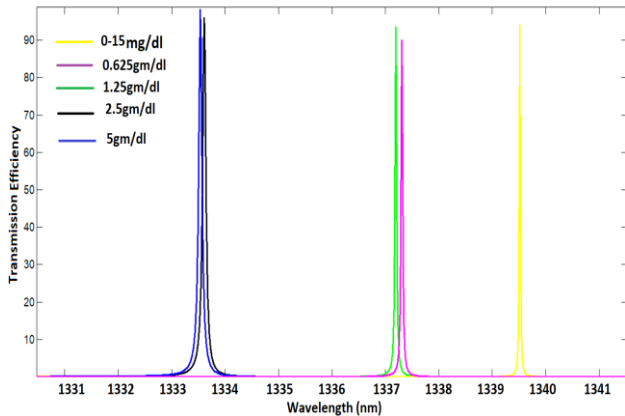


Figure 9: Urine glucose concentration analysis with horizontal loop double ring resonator

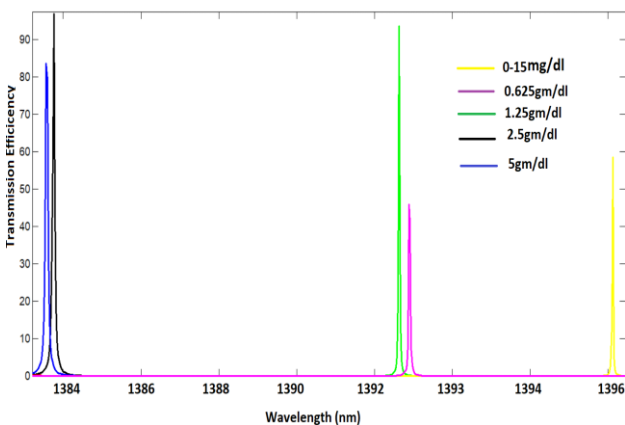


Figure 10: Urine glucose concentration analysis with vertical loop double ring resonator

Table IV: Urine glucose concentration and transmission spectrum data - Horizontal loop double ring resonator

Glucose concentration in urine	Refractive Index	Resonant wavelength	Transmission efficiency	Q Factor
Normal (0-15gm/dl)	1.335	1333.5	98	12323
0.625gm/dl	1.336	1333.6	98	12112
1.25gm/dl	1.337	1337.5	98	12212
2.5gm/dl	1.338	1337.6	92	12343
5gm/dl	1.346	1396	98	12311

Table V: Urine glucose concentration and transmission spectrum data - Vertical loop double ring resonator

Glucose concentration in urine	Refractive Index	Resonant wavelength	Transmission efficiency	Q Factor
Normal (0-15gm/dl)	1.335	1383	82	10112
0.625gm/dl	1.336	1383.8	99	10254
1.25gm/dl	1.337	1392.5	98	10121
2.5gm/dl	1.338	1392.8	50	10223
5gm/dl	1.341	1396	60	10234

Figure 5 and Figure 6 shows the transmission spectrum obtained for horizontal loop double ring resonator and vertical loop double ring resonator for detecting the glucose concentration in blood. Transmission spectrum is observed with wavelength range of 1235.5nm to 1237nm and 1096nm to 1097nm respectively. Maximum transmission efficiency 98% obtained for horizontal loop ring resonator structure and transmission efficiency obtained for vertical loop ring resonator structure was less compared to horizontal loop. In case of glucose concentration in urine detection process maximum transmission efficiency of above 90% is observed in the case of horizontal loop ring resonator structure. The amount of light transmitted in the sensing structure is referred as transmission efficiency. Difference between wavelength shift obtained was minimum in case of horizontal loop ring resonator structure during the detection of glucose concentration in urine. Maximum sensitivity of 5681nm/RIU is obtained for horizontal loop double ring resonator structure. Table VI shows the comparison between presented work and reported sensors. Proposed sensor is compared with different photonic sensing configurations designed for different applications. Sensing structures considered in recently published articles has shown less sensitivity compared to proposed sensor.

Table VI: Comparison between proposed and reported sensor

Ref	Year	Work considered	Sensitivity
10	2021	Graphene-based 1D defective photonic crystal	290nm/RIU
11	2021	Photonic Crystal for Malaria Diagnosis	495nm/RIU
12	2021	Highly Sensitive 1D Photonic Crystal Biosensor	440nm/RIU
13	2021	Malaria in RBC using Photonic biosensor	225nm/RIU
14	2021	Biomolecule detection in blood and urine	400nm/RIU
-	2022	Present work	5681nm/RIU

IV. CONCLUSION

Proposed work consists of design and analysis of two different type of ring resonator structure for finding amount of glucose present in bio sample obtained by patients. Proposed work on optical sensor design can be used for invasive and noninvasive method of glucose detection in future i.e. invasive as blood and non-invasively as urine. Horizontal and vertical loop double ring resonant structure are considered in this work. Band gap range of Horizontal and vertical loop double ring resonant structure is 900nm to 1400nm and 1080nm to 1400nm respectively. Maximum Q factor obtained 12343 for horizontal loop ring resonator structure. Maximum sensitivity obtained was 5681nm/RIU. High transmission efficiency obtained for horizontal loop structure. Results obtained shows future fabrication feasibility.

REFERENCES

[1] American Diabetes Association. 7. Diabetes technology: standards of medical care in diabetes—2021. *Diabetes Care*. 2021;44(suppl 1):S85-S99. https://care.diabetesjournals.org/content/44/Supplement_1/S85.

[2] Takuro Tajima, Masahito Nakamura, Yujiro Tanaka, Michiko Seyama, *Advances in Noninvasive Glucose Sensing Enabled by Photonics, Acoustics, and Microwaves*, International Journal of Automation Technology, 2018, Volume 12, Issue 1, Pages 64-72, Released November 05, 2018, Online ISSN 1883-8022, Print ISSN 1881-7629, <https://doi.org/10.20965/ijat.2018.p0064>.

[3] S. Ameta, A. Sharma and P. K. Inaniya, "Designing a multichannel nanocavity coupled photonic crystal biosensor for detection of glucose concentration in blood," 2017 8th International Conference on Computing, Communication and Networking Technologies (ICCCNT), 2017, pp. 1-4, doi: 10.1109/ICCCNT.2017.820400

[4] Robinson, S., Dhanlaksmi, N. Photonic crystal-based biosensor for the detection of glucose concentration in urine. *Photonic Sensor*, 7, 11–19 (2017). <https://doi.org/10.1007/s13320-016-0347-3>

[5] Rahaman, M., Jibon, R.H., Ahsan, M. et al. Glucose Level Measurement Using Photonic Crystal Fiber-based Plasmonic Sensor. *Plasmonics* (2021). <https://doi.org/10.1007/s11468-021-01497-4>

[6] Ali Rashidnia, H Pakarzadeh, Mohsen Hatami, Natesan Ayyanar, Photonic Crystal-Based Biosensor for Detection of Human Red Blood Cells Parasitized by Plasmodium Falciparum, *Optical and Quantum Electronics*, Research Square, 2021, 10.21203/rs.3.rs-655711/v1.

[7] Inan H, Poyraz M, Inci F, et al. Photonic crystals: emerging biosensors and their promise for point-of-care applications. *Chem Soc Rev*. 2017;46(2):366-388. doi:10.1039/c6cs00206d.

[8] A. K. Paul, A. K. Sarkar and S. M. A. Razzak, "Graphene coated photonic crystal fiber biosensor based on surface plasmon resonance,"

2017 IEEE Region 10 Humanitarian Technology Conference (R10-HTC), 2017, pp. 856-859, doi: 10.1109/R10-HTC.2017.8289088.

[9] Nouman, W.M., Abd El-Ghany, S.E.S., Sallam, S.M. et al. Biophotonic sensor for rapid detection of brain lesions using 1D photonic crystal. *Opt Quant Electron* 52, 287 (2020). <https://doi.org/10.1007/s11082-020-02409-2>.

[10] Manjunath Managuli, Abhay Deshpande., "Description and Identification of Soil Quality Measuring Development using Uav's and E-Nose System" *International Journal of Recent Technology and Engineering*, Elsevier Scopus Index, Volume-8, Issue-3 September 2019. DOI: 10.35940/ijrte.C5276.098319.

[11] Panda, A., Pukhrabam, P.D., Wu, F. et al. Graphene-based 1D defective photonic crystal biosensor for real-time detection of cancer cells. *Eur. Phys. J. Plus* 136, 809 (2021). <https://doi.org/10.1140/epjp/s13360-021-01796-z>

[12] Ankita, Suthar, B. & Bhargava, A. Biosensor Application of One-Dimensional Photonic Crystal for Malaria Diagnosis. *Plasmonics* 16, 59–63 (2021). <https://doi.org/10.1007/s11468-020-01259-8>

[13] M. S. S. Ibrahim, M. Tarek, S. S. A. Obayya and M. F. O. Hameed, "Highly Sensitive 1D Photonic Crystal Biosensor," 2021 International Applied Computational Electromagnetics Society Symposium (ACES), 2021, pp. 1-2, doi: 10.1109/ACES53325.2021.00089.

[14] Kumar, B.M.H., Srikanth, P.C. & Vaibhav, A.M. A novel computation method for detection of Malaria in RBC using Photonic biosensor. *Int. j. inf. tecnol.* (2021). <https://doi.org/10.1007/s41870-021-00782-z>

[15] Manjunath Managuli, Abhay Deshpande., "A role of Electronic nose system Information gathering with smart phone" *Materials Today*, Elsevier, Volume-43, Part-6, Page No. 3404- 3408, April-2021. DOI: 10.1016/j.matpr.2020.09.069.

[16] P.R. Yashaswini, H.N. Gayathri, P.C. Srikanth, Performance analysis of photonic crystal based biosensor for the detection of bio-molecules in urine and blood, *Materials Today: Proceedings*, 2021, ISSN 2214-7853, <https://doi.org/10.1016/j.matpr.2021.06.192>.

[17] J. D. Joannopoulos, P. R. Villeneuve, and S. Fan, "Photonic crystals: Putting a new twist on light," *Nature*, vol. 386, no. 6621, pp. 143–149, 1997.

[18] R. D. Meade, A. M. Rappe, K. D. Brommer, and J. D. Joannopoulos, "Existence of a photonic band gap in two dimensions," *Appl. Phys. Lett.*, vol. 61, no. 4, pp. 495–497, 1992.

[19] Manjunath Managuli, Abhay Deshpande., "Automated Food Quality Technique using Electronic nose System" *Test Engineering & Management*, Vol. 82, Issue 13, Page No. 11852-11856 Feb-2020.

[20] X. Fan, I. M. White, S. I. Shopova, H. Zhu, J. D. Suter, and Y. Sun, "Sensitive optical biosensors for unlabeled targets: A review," *Anal. Chim. Acta*, vol. 620, nos. 1–2, pp. 8–26, 2008.

[21] P. Sharma, S. K. Roy, and P. Sharan, "Design and simulation of photonic crystal based biosensor for detection of different blood components," in *Proc. IEEE Region 10 Symp.*, Kuala Lumpur, Malaysia, Apr. 2014, pp. 171–176.

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

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

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

[25] Manjunath Managuli, Abhay Deshpande., "Implementation of Electronic nose system by using quad captor" *International Journal of Advanced Science & Technology*, Vol. 29, Issue 9s, Page No. 6823-6832, 2020.

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

[27] 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.

- [28] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic crystal: modeling of flow of light*. Princeton: Princeton University Press, 1995
- [29] Lin, T.; Gal, A.; Mayzel, Y.; Horman, K.; Bahartan, K. Non-invasive glucose monitoring: A review of challenges and recent advances. *Curr. Trends Biomed. Eng. Biosci.* 2017, 6, 1–8.