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Design and simulation of a photonic crystal sensor for accurate blood plasma diagnostics

Manisha Chakrabarti Chattopadhyay[1,2], Rajib Chakraborty[2], Tapanendu Kundu[3]
[1]Department of Electronics and Telecommunication, Vivekanand Education Society Institute of Technology, Mumbai, India
[2]Department of Applied Optics and Photonics, University of Calcutta, Kolkata, India
[3]Department of Physics, Indian Institute of Technology Bombay, Mumbai, India

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ABSTRACT

Photonic crystals (PC) are materials with periodic refractive index variations, resulting in photonic band gaps that allow light propagation across specific frequencies. PC-based sensors have gained significant attention in the scientific community for their diverse applications in biomedical sensing. This research presents the design of a novel blood plasma PC-based sensor that utilizes a 532 nm laser light source. The sensor incorporates defects within a 2D crystal, enabling precise modification of its characteristics based on the specific type of impurity introduced. The designed sensor, when simulated, demonstrates the ability to effectively detect both regular and infected blood plasma, with the potential for identifying diverse plasma types. Through optimization of device parameters, the sensor achieves optimal sensitivity of 12.5 nm per refractive index unit (RIU), utilizing a 75% defect relative to the total height of the device, which measures 278.46 nm. This sensitivity makes it well-suited for accurate diagnostics in low-volume blood plasma testing. The proposed sensor exhibits versatility and holds promise for potential utilization in a variety of diagnostic applications that necessitate minimal sample volume and high sensitivity requirements.

Corresponding Author:

Manisha Chakrabarti Chattopadhyay
Department of Electronics and Telecommunication, Vivekanand Education Society Institute of Technology
Mumbai, India
Email: Manisha.chattopadhyay@ves.ac.in

1. INTRODUCTION

Photonic crystals (PCs) are a group of materials that display periodic fluctuations in their refractive index, leading to the creation of photonic band gaps that prevent light from propagating across specific frequency ranges [1]. PCs have garnered considerable attention in both scientific and technological domains due to their diverse applications in optics, optoelectronic devices, and chemical as well as biomedical sensing [2]. The periodic variation of the refractive index profoundly affects various spectral properties, including reflectance, transmittance, band structure, group velocity, and the rate of spontaneous emission. This allows PCs to manipulate and control light propagation in a variety of ways, making them useful in many areas [3].

PC-based sensors have already proven to be effective in chemical, biological, gas, and temperature detection applications, thanks to their compact size and real-time monitoring ability [4]. PCs have also been used for developing various photonic devices such as filters, lasers, and optical switches [5]. Furthermore, PCs offer a range of possibilities for the creation of unique electromagnetic properties such as negative refraction, which is useful in designing for imaging with a resolution beyond the diffraction limit [6].

Blood plasma is the liquid component of blood, comprising proteins, antibodies, enzymes, electrolytes, hormones, and other essential nutrients [7]. It plays a pivotal role in upholding the body's pH

balance, facilitating nutrient transportation, and eliminating waste products [8]. Given its wealth of information about a patient's health status, blood plasma finds extensive use in diagnostics [9]. It enables the measurement of protein and hormone levels, electrolyte balance, as well as the detection of infections or diseases [10].

Plasma diagnostics presently rely on costly techniques. These include retarding field analyzers, magnetic probes, Langmuir probes, and self excited electron plasma resonance spectroscopy (SEERS) [11]. Proton radiography is sometimes used to measure magnetic and electric fields in the plasma [12].

In medical applications, one dimensional photonic crystal (1D PC) structures have proven to be highly valuable, particularly for blood plasma-based diagnostics [13]. The distinct refractive index values of various blood plasma constituents offer great utility in disease detection, clinical diagnoses, metabolic regulation, and biochemical analysis for diverse medical purposes [14]. Utilizing 1D PC structures enables the measurement of different blood plasma concentrations [15]. These structures can be fabricated through spin coating, forming multi-layers, and employing both harder and softer materials using dip-coating approaches [16].

To examine the plasma refractive index variation sensing mechanism of 1D PCs, we employed a well-defined PC structure with a defect layer, as depicted in Figure 1. The defect induced a reflection dip at the specific wavelength of 532 nm [17]. For biosensing purposes, a sensing slot was introduced in the defect region, and we varied the height of the defect layer to observe changes in reflection characteristics and central wavelength [18].

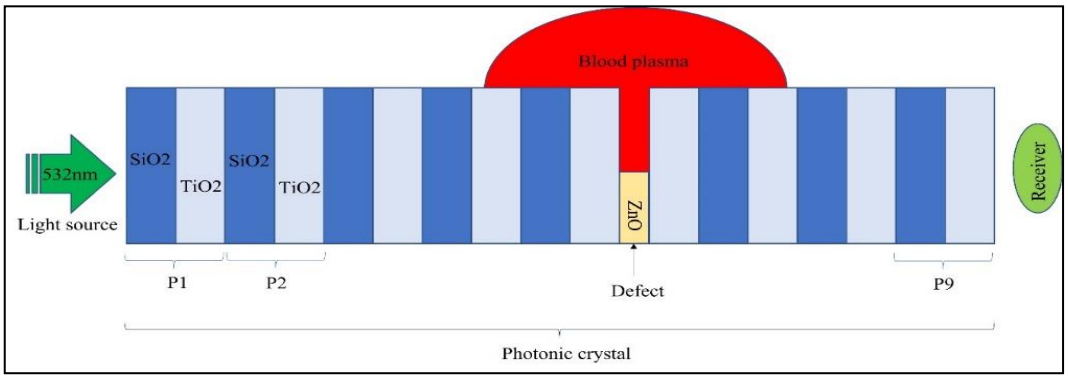


Figure 1. A novel bio-photonic sensor composed of a 1D PC with defect, has been explored for the purpose of blood plasma analysis

There are many researchers who used PCs for blood sensing applications in recent years. Gandhi *et al*. [19] developed a biophotonic sensor using a one-dimensional defective annular photonic crystal based on porous silicon. This sensor effectively detected changes in the refractive index of blood serum samples with varying creatinine concentrations, exhibiting high sensitivity, quality factor, and figure of merit.

Ghany *et al*. [20] designed a sensor to measure blood hemoglobin levels using a defected one-dimensional photonic crystal. They optimized the structure by adjusting the angle of incidence, the thickness of the defect layer, and the refractive index of the first layer. They achieved an average sensitivity of approximately 1025 nm/RIU.

Bijalwan *et al*. [21] created a one-dimensional photonic crystal-based sensor for detecting blood plasma and cancer cells. The sensor comprised a sample layer sandwiched between two identical PCs made of silica and titania. Their transfer matrix method evaluation yielded a sensitivity of 71.25 nm/RIU for a 100 nm sample thickness, which could be increased to 161 nm/RIU by increasing the sample thickness to 300 nm. The sensor successfully detected cancer cells and hemoglobin in blood plasma with sensitivities exceeding 73 nm/RIU and 72 nm/RIU, respectively.

Other researchers have investigated different photonic crystal-based architectures in the field of biomedical applications. For instance, John and Wang [22] focused on optimizing a three-dimensional metallic photonic-band-gap filament architecture. This particular architecture aimed to achieve electrically pumped, quasi-thermal, visible light emission.

Kazempour and Vahed [23] proposed a D-shaped plasmonic optical biosensor. It is based on photonic crystal fiber (PCF) and can detect various materials such as water, blood plasma, and hemoglobin. Sharma *et al*. [11] developed a 2-D photonic crystal double-ring resonator-based biosensor. This biosensor is specifically designed for detecting the chikungunya virus. It can detect the virus in normal and infected plasma, platelets, red blood cells, and uric acid in the blood.

Khozondar *et al*. [24] introduced a one-dimensional ternary photonic crystal. They incorporated defects or cavity cells infiltrated with blood samples and surrounded them with graphene layers in the middle region. This design aimed to preserve the characteristics of the blood samples during testing. Jalil *et al.* [25] focused on optimizing the PC structure to detect blood plasma and enhance device sensitivity. They achieved this by tuning the PC structure to observe the transmittance spectrum in the infrared region. Their objective was to improve the detection of blood plasma and optimize the performance of the device.

2. METHOD

Figure 2 shows the setup for the COMSOL simulation. The blue-colored region above the structure (structure represented in gray) consisted of either air, water, or plasma depending on the experiment. The blue regions below, front, and in the back side of the gray main structure consist of air. The defect height of 25% is presented for demonstration purposes only, as during actual experiments, we varied these heights in three steps: 25%, 50%, and 75%. Additionally, we conducted initial experiments with 100% defect to establish the sharp bandpass filtering at 532 nm.

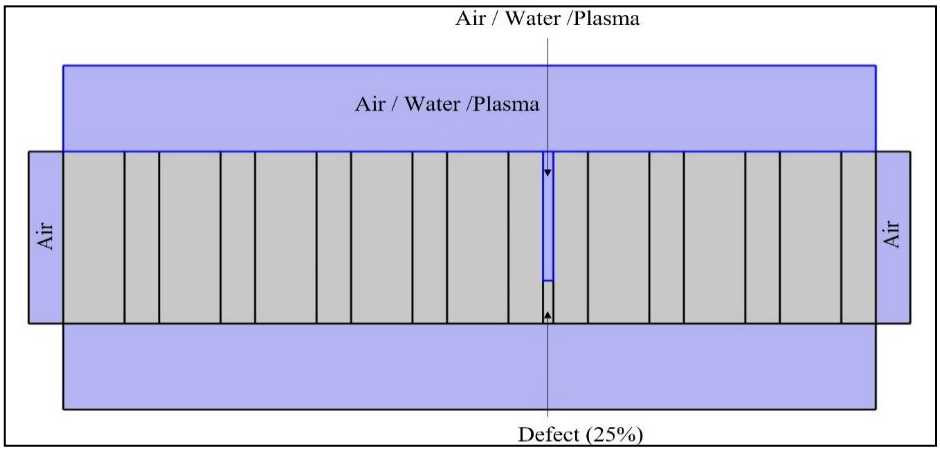


Figure 2. COMSOL simulation setup of a 1D PC representing different regions

The reflection coefficient drops significantly at about 532 nm wavelength when a defect of 100% is introduced in the 6th layer, as shown in Figure 3. The defect also transforms the wide band stop filter into a sharp bandpass filter. This principle forms the basis of the proposed plasma sensor design.

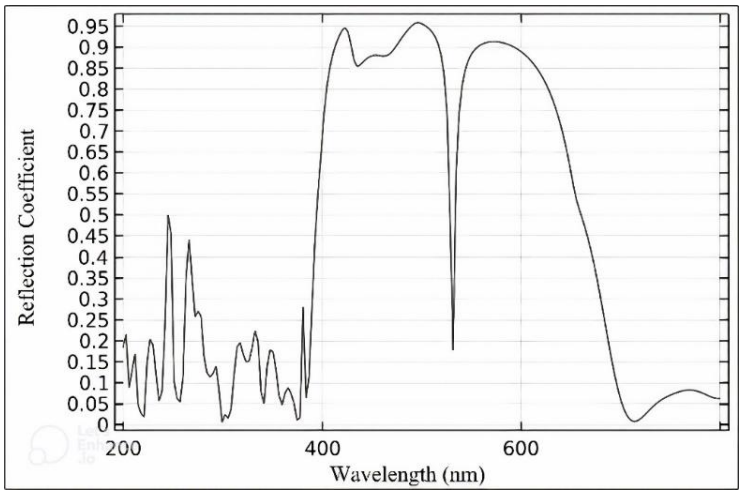


Figure 3. Graph showing the reflection coefficient plotted against wavelength. A pronounced dip in the spectrum occurs at around 532 nm, resulting from a 100% defect in the structure

3. RESULTS AND DISCUSSION

We have changed the defect layer height from 25% to 100% in steps of 25%. The defect height was varied and the sensing region is filled with the liquid of interest. We found out at 25% of the height of the defect layer (with reflection coefficient minima of 0.1875 at a wavelength of 532.06 nm). The 50% defect layer height gave 0.18739 reflection coefficient minima with a wavelength of 532.06 nm. For the 75% defect layer height the reflection coefficient minima were 0.18527 at a wavelength of 532.06 nm). To determine the best defect layer height, we used water as a medium in the second half of the defect.

Figure 4 illustrates the impact of height variation between the defect and the sample (blood plasma). The defect was introduced at four different heights, ranging from a 100% defect down to a 25% defect in increments of 25%. Our observations revealed that the most significant drop in reflection coefficient occurred when the defect occupied 75% of the space, with the remaining 25% filled with plasma.

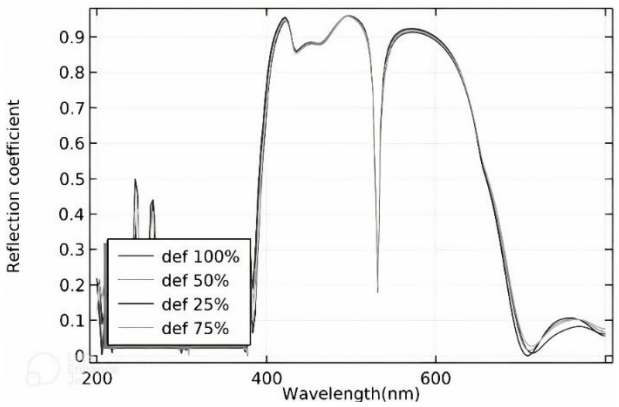
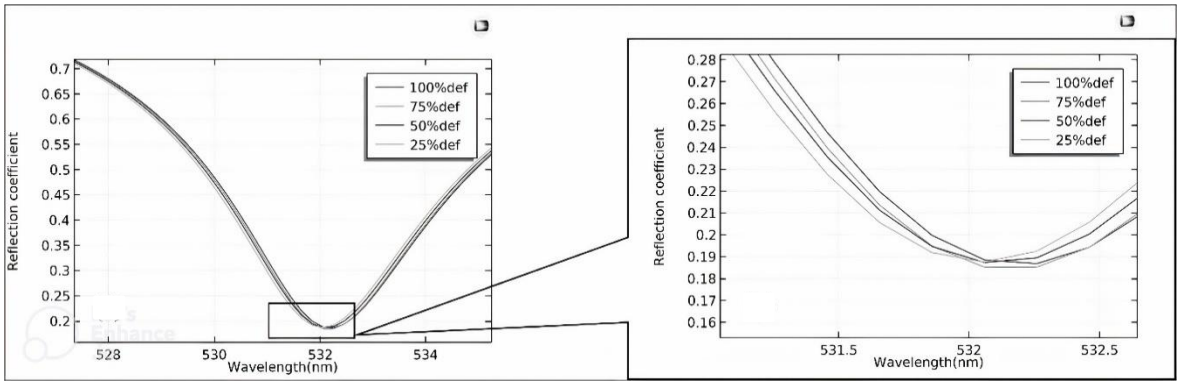


Figure 4. Effect of height variation between defect and sample (blood plasma)

We have varied the refractive index values of this region ranging from 1.33 (water/non-infected plasma) to 1.41 (infected blood plasma for the infected patient). Figure 5 exhibits the plot of wavelength versus reflection coefficient, focusing on two specific ranges. Firstly, in range Figure 5(a) from 528 nm to 536 nm as shown in Figure 5(a), and secondly, in range Figure 5(b) magnified between 531.5 nm and 532.5 nm as shown in Figure 5(b). Through careful examination of these plots, a conspicuous observation emerges. It becomes evident that a pronounced 75% defect dip occurs at the minima, highlighting its status as the most defective point. Remarkably, the reflection coefficient can plummet as low as 0.18527, indicating the extent of the defect's impact. These findings underscore the significance of the plotted data, shedding light on the nature and severity of the defect in terms of wavelength and reflection coefficient.



(a) (b)

Figure 5. The plot of wavelength versus reflection coefficient within a limited range of (a) 528 nm to 536 nm wavelength and (b) magnified to 531.5 nm to 532.5 nm. It was evident from the plots that 75 % defect has the largest dip i.e., minima proving it to be the most sensitive defect

Figure 6 presents a detailed wavelength-reflection coefficient plot, illustrating the distinctive features of water or Non-infected blood plasma (Refractive inde=1.33) and infected blood plasma (Refractive index=1.41) samples. In this plot, 75% of the space is occupied by an impurity zinc oxide (ZnO), while the remaining 25% is filled with either water or blood plasma. Notably, at a wavelength of 532.06 nm, a significant dip is observed in the reflection coefficient for water/non-infected blood plasma, indicating a specific behavior. However, for infected blood plasma, the dip shifts slightly to 532.66 nm, suggesting a variation in its reflective properties. The minimum reflection coefficient for water/non-infected blood plasma is precisely measured at 0.18527, while for infected blood plasma, it shifts to 0.22073, signifying a disparity in their reflective characteristics. This detailed analysis provides valuable insights into the distinct behavior of water/non-infected blood plasma and infected blood plasma in terms of wavelength and reflection coefficients. This allows the device to work as an identifier for different types of plasma.

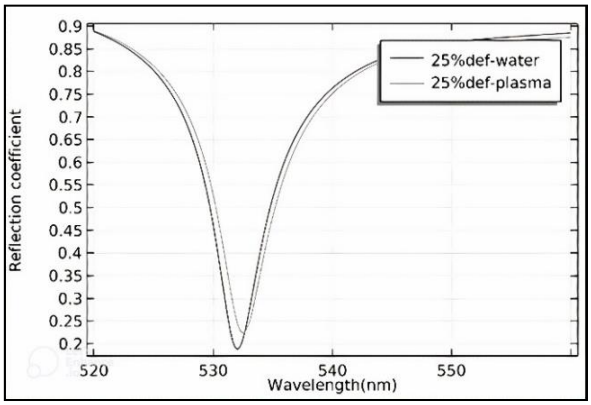


Figure 6. Wavelength-reflection coefficient plot showcasing the characteristics of water and plasma samples

The experiment utilized a SiO2-TiO2 photonic crystal structure with defect layers of ZnO. The defects introduced had different heights and refractive indices varied because of the sample inserted in the gap created. The sensing region was exposed to various blood plasma samples with differing refractive indices, and these samples were characterized in comparison to air and water. Reflective coefficients were observed in relation to wavelength for different defect height variations and sensing materials, specifically blood plasma. Upon reviewing the existing literature, it was found that most previous research focused on multicomponent analysis using photonic crystals, whereas this study concentrated solely on cancer-infected blood plasma. Future research could investigate other blood plasma diseases.

Many researchers have employed a photonic crystal ring resonator for blood plasma measurements. However, our proposed sensor design allows for wavelength fine-tuning, unlike the photonic crystal optical ring resonator, which is limited to a single wavelength. In the literature, a reported sensitivity of 72 nm/RIU was found, which was a significant difference compared to our proposed design, we achieved a 12.5 nm shift per RIU. As a result, a single optical source transmission should be sufficient for measuring the entire shift caused by the disease.

This study introduced a novel blood plasma sensor design that leverages a 532 nm laser light source. The sensor's principle of operation involves the introduction of impurities into a 2D photonic crystal, altering the device's characteristics based on the type of impurity. Notably, the proposed sensor can detect both regular and infected blood plasma, offering a versatile solution for identifying various plasma types. The designed structure demonstrated a maximum sensitivity of 12.5 nm per RIU with 75% defect and 25% sample of the total device height at 278.46 nm. Additionally, the proposed sensor has potential applications in other diagnostic areas requiring minimal sample volume and high sensitivity measurements, making it particularly suitable for low-volume blood plasma testing.

4. CONCLUSION

In this research paper, we present a novel design for a blood plasma PC-based sensor optimized for a 532 nm laser light source. The sensor operation is based on introducing defect into a 2D photonic crystal, leading to characteristic changes depending on the type of impurity added. Notably, our proposed sensor can detect both regular and infected blood plasma, making it a versatile tool for identifying various types of plasma.

The designed structure exhibits a maximum sensitivity of 12.5 nm per RIU when incorporating 75% defect and 25% sample of the total device height at 278.46 nm. We believe that this device has great potential for diverse diagnostic applications requiring minimal sample volume and high-sensitivity measurements. Specifically, it is well-suited for low-volume blood plasma testing. This innovative sensor offers promising prospects for advancing biomedical diagnostics and improving healthcare outcomes.

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REFERENCES

[1] M. Shaban, A. M. Ahmed, E. Abdel-Rahman, and H. Hamdy, "Tunability and sensing properties of plasmonic/1D photonic crystal," *Scientific Reports*, vol. 7, no. 1, p. 41983, Feb. 2017, doi: 10.1038/srep41983.

[2] J. Zhang, Q. Zou, and H. Tian, "Photochromic materials: more than meets the eye," *Advanced Materials*, vol. 25, no. 3, pp. 378–399, Jan. 2013, doi: 10.1002/adma.201201521.

[3] M. R. Rakhshani and M. MansouriBirjandi, "Tunable channel drop filter using hexagonal photonic crystal ring resonators," *TELKOMNIKA (Telecommunication, Computing, Electronics and Control)*, vol. 11, no. 1, pp. 513-516, Jan. 2013, doi: 10.11591/telkomnika.v11i1.1788.

[4] R. Purbakawaca, A. S. Yuwono, H. Alatas, and I. D. M. Subrata, "Low-cost nitrogen dioxide monitoring station based on metal oxide sensor and cellular network," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 26, no. 1, pp. 105–115, 2022, doi: 10.11591/ijeecs.v26.i1.pp105-115.

[5] G. J. Tang, X. T. He, F. L. Shi, J. W. Liu, X. D. Chen, and J. W. Dong, "Topological photonic crystals: physics, designs, and applications," *Laser and Photonics Reviews*, vol. 16, no. 4, p. 2100300, Apr. 2022, doi: 10.1002/lpor.202100300.

[6] S. Bendib and C. Bendib, "Photonic crystals for malaria detection," *Journal of Biosensors & Bioelectronics*, vol. 09, no. 03, 2018, doi: 10.4172/2155-6210.1000257.

[7] Z. A. Zaky, B. Moustafa, and A. H. Aly, "Plasma cell sensor using photonic crystal cavity," *Optical and Quantum Electronics*, vol. 53, no. 10, p. 591, Oct. 2021, doi: 10.1007/s11082-021-03201-6.

[8] P. Sharma and P. Sharan, "Design of photonic crystal-based biosensor for detection of glucose concentration in urine," *IEEE Sensors Journal*, vol. 15, no. 2, pp. 1035–1042, Feb. 2015, doi: 10.1109/JSEN.2014.2359799.

[9] E. Podder, M. B. Hossain, M. E. Rahaman, A. A. M. Bulbul, and K. Ahmed, "Design and optimization of terahertz blood components sensor using photonic crystal fiber," *Sensing and Bio-Sensing Research*, vol. 30, p. 100386, Dec. 2020, doi: 10.1016/j.sbsr.2020.100386.

[10] N. D. Astuti, J. Suparyatmo, and A. Kurniati, "Diagnostic test of serum pregnancy-associated plasma protein-a level as biomarker for early diagnosis of acute myocardial infarction," *Indonesian Journal of Clinical Pathology and Medical Laboratory*, vol. 26, no. 3, pp. 297–302, Sep. 2020, doi: 10.24293/ijcpml.v26i3.1578.

[11] S. Sharma, A. Kumar, K. S. Singh, and H. K. Tyagi, "2D photonic crystal based biosensor for the detection of chikungunya virus," *Optik*, vol. 237, p. 166575, Jul. 2021, doi: 10.1016/j.ijleo.2021.166575.

[12] M. Borghesi *et al.*, "Electric field detection in laser-plasma interaction experiments via the proton imaging technique," *Physics of Plasmas*, vol. 9, no. 5, pp. 2214–2220, May 2002, doi: 10.1063/1.1459457.

[13] A. P. Drabovich, P. Saraon, K. Jarvi, and E. P. Diamandis, "Seminal plasma as a diagnostic fluid for male reproductive system disorders," *Nature Reviews Urology*, vol. 11, no. 5, pp. 278–288, May 2014, doi: 10.1038/nrurol.2014.74.

[14] D.-W. Yeh and C.-J. Wu, "Thickness-dependent photonic bandgap in a one-dimensional single-negative photonic crystal," *Journal of the Optical Society of America B*, vol. 26, no. 8, p. 1506, Aug. 2009, doi: 10.1364/josab.26.001506.

[15] F. Segovia-Chaves and H. Vinck-Posada, "Dependence of the transmittance spectrum on temperature and thickness of superconducting defects coupled in dielectric one-dimensional photonic crystals," *Optik*, vol. 170, pp. 384–390, Oct. 2018, doi: 10.1016/j.ijleo.2018.05.109.

[16] H. Tian and Y. Ji, "Effect of defect layer thickness on slow light in one-dimensional photonic crystals," *Modern Physics Letters B*, vol. 23, no. 8, pp. 1053–1062, Mar. 2009, doi: 10.1142/S0217984909019284.

[17] J. Martorell, R. Vilaseca, and R. Corbalán, "Second harmonic generation in a photonic crystal," *Applied Physics Letters*, vol. 70, no. 6, pp. 702–704, Feb. 1997, doi: 10.1063/1.118244.

[18] W. A. Shehab, A. Salah, W. Al-Sawalmeh, and H. Alashaary, "Few-mode optical fiber surface plasmon resonance sensor with controllable range of measured refractive index," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 13, no. 1, pp. 454–464, 2023, doi: 10.11591/ijece.v13i1.pp454-464.

[19] S. Gandhi, S. K. Awasthi, and A. H. Aly, "Biophotonic sensor design using a 1D defective annular photonic crystal for the detection of creatinine concentration in blood serum," *RSC Advances*, vol. 11, no. 43, pp. 26655–26665, 2021, doi: 10.1039/d1ra04166e.

[20] S. E. S. A. El-Ghany, W. M. Noum, Z. S. Matar, Z. A. Zaky, and A. H. Aly, "Optimized bio-photonic sensor using 1D-photonic crystals as a blood hemoglobin sensor," *Physica Scripta*, vol. 96, no. 3, p. 035501, Dec. 2021, doi: 10.1088/1402-4896/abd49c.

[21] A. Bijalwan, B. K. Singh, and V. Rastogi, "Analysis of one-dimensional photonic crystal based sensor for detection of blood plasma and cancer cells," *Optik*, vol. 226, p. 165994, Jan. 2021, doi: 10.1016/j.ijleo.2020.165994.

[22] S. John and R. Wang, "Metallic photonic-band-gap filament architectures for optimized incandescent lighting," *Physical Review A - Atomic, Molecular, and Optical Physics*, vol. 78, no. 4, p. 043809, Oct. 2008, doi: 10.1103/PhysRevA.78.043809.

[23] M. V. Kazempour and H. Vahed, "Plasmonic D-shaped photonic crystal fiber biosensor with gold layer for sensing of the refractive index," *International Journal of Optics and Photonics*, vol. 14, no. 2, pp. 209–216, Dec. 2020, doi: 10.52547/ijop.14.2.209.

[24] H. J. El-Khozondar, P. Mahalakshmi, R. J. El-Khozondar, N. R. Ramanujam, I. S. Amiri, and P. Yupapin, "Design of one dimensional refractive index sensor using ternary photonic crystal waveguide for plasma blood samples applications," *Physica E: Low-Dimensional Systems and Nanostructures*, vol. 111, pp. 29–36, Jul. 2019, doi: 10.1016/j.physe.2019.02.030.

[25] R. Jalil, A. Sabbar, H. F. Fakhruldeen, and F. I. Jabbar, "Design and implementation of PC to PC data transmission using wireless visible light communication system," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 26, no. 3, pp. 1423–1428, 2022, doi: 10.11591/ijeecs.v26.i3.pp1423-1428.

BIOGRAPHIES OF AUTHORS

Manisha Chakrabarti Chattopadhyay is Pursuing Ph.D. From the Department of Applied Optics and Photonics University of Calcutta. Total teaching experience 25 years. Working as Associate Professor in Vivekananda education society institute of Technology, Chembur, Mumbai -74. Published and presented multiple papers in several national and international conferences and journals. Her research areas include fiber optic systems, antenna designing, photonics optical waveguides. She can be contacted at email: manisha.chattopadhyay@ves.ac.in.

Rajib Chakraborty is currently working as a Professor at the Department of Applied Optics and Photonics University of Calcutta. He has published many 95 journal articles 5 sponsored projects handled. His research areas are integrated Optical devices, MEMS and nanophotonic structures, periodic poling for acousto-optical memory devices, and designing of integrated optical and nanophotonic devices, processing of fiber-optic based sensors, micromachining of optical materials and optical fibers using laser and diamond-like nanocomposite surface coating technology. Total teaching experience is 20 years. He is a life member of prestigious and renowned professional societies like the Optical Society of India Optical Society of America (OSA) SPIE Honorary Treasurer, Optical Society of India, Reviewer: IEEE, OSA, SPIE, Elsevier, Springer, Hindawi. He can be contacted at email: rcaphy@caluniv.ac.in.

Tapanendu Kundu is currently working as a Professor at the Department of Physics and Dean of Students Welfare at IIT Bombay. He has published many 87 journal articles, 1 book chapter 19 conference proceedings, and 13 patents. His research areas are applied physics, laser spectroscopy, non-linear spectroscopy, photoacoustic spectroscopy, and non-linear optics. Total teaching experience is 38 years. He can be contacted at email: tkundu@phy.iitb.ac.in.