Exp. Theo. NANOTECHNOLOGY 3 (2019) 437-446 https://doi.org/10.56053/3.3.437

Theoretical studies on hemoglobin periodic structure sensor

Arafa H Aly[1,], Walaa M. Nouman[2], S.E.-S. Abd El-Ghany[2], Samira M.Sallam[2], Abdel-Fattah B. Dawood[2]*

[1]TH-PPM Group, Physics department, Faculty of Science, Ben-Suef University, Egypt
[2]Physics department, Faculty of Science, Benha University, Egypt
*) E-mails: arafa.hussien@science.bsu.edu.eg, arafa16@yahoo.com

Received 25/5/2018, *Accepted* 9/8/2019, *Published* 15/9/2019

In the present study, we have obtained a blood hemoglobin (Hb) sensor using binary defective one-dimensional photonic crystal. The structure is composed of Air/Diamond/SiO_2)^{N}Hb /Diamond/SiO_2)^S/SiO_2 and the defect layer is filled by hemoglobin solution. The numerical calculations are based on transfer matrix method (TMM). The defect peak showed well shifting of the defect peak frequency by increasing the hemoglobin concentration; the wavelength shifted due to the change of hemoglobin concentration; from 679.5 nm at the 0g/dL to 682.3 nm at 28.7 g/dL. The presented idea is very simple, and can potentially attract a wider audience when one considers the fact of constantly rising interest of the scientific community (especially biologists and physicians) in the diagnostic methods utilizing different types of the optical phenomena.

1. INTRODUCTION

The wave's propagation through complex media plays a critical role in many areas of physical sciences [1]. A good example of these media is photonic crystals. The term photonic crystal (PCs) was formed in 1987 after Yablonovitch [2] and John [3] had their first meeting in Princeton. PCs are micro/Nanostructures which composed of spatial, periodic arrangement of dielectric materials with the high variation of refractive index. According to the geometry of structures, there are three types of PC structures are one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D). 1D PCs or called multilayer structures have a periodicity of refractive index in one direction but homogeneous in other two directions [4-9]. 1D PCs have a large number of applications by embedded one or more defect layers through periodic layers [10-15].2D PCs are structures in which refractive index is varied in two directions while there is no variation in the third direction .3D- PCs are those in which periodicity of refractive index is in three directions. PCs take their importance from the creation of photonic band gaps (PBG) in which frequency ranges of incident light are prohibited inside PCs. A large PBG is the backbone for various applications such as the omnidireoctional high reflectors, high-Q microcavities, low threshold lasers, optical switches, and optical transistors [16, 17].

In the biological/chemical analysis, PCs play an essential role as label-free sensor since any changes in refractive index and /or thickness of the composing materials effect on the interaction of the PCs with analyte/fluid to be identified [18, 19]. Many devices of label-free sensor based on 1D, 2D, and 3D PCs are designed by using different materials such as Silicon, TiO2 [20, 21]. For example, 1D silicon photonic crystal with an air defect is designed by Mohebbi [22] to oscillate at a single mode with a high-quality factor, allowing for refractive index sensing of gases with a high sensitivity. Photonic crystals are indeed a promising sensor platform. Since they can be used for analyzing liquid systems PCs are interesting for biosensing. Hb is one of the substances of general interest; hence the aim of the paper is justifies both additional efforts and publication. In recent days different types of PCs are used in biosensing field such as gene chips [23,24], blood glucose sensor [25], diabetes and blood disorders [26]. It is worth mentioning these devices have many advantages are low cost, used low energy and provide measurements directly, in contrast, conventional methods which take a long time [27].

In this paper, we design a biosensor device based on 1D-defected binary PCs which is composed of ten periodic dielectric layers with hemoglobin solution as defect layer. It’s known that a unique feature of PCs caused by the variations in index of refraction of constituent materials. As a result, we used Diamond and Silicon dioxide layers with high and low refractive index respectively and the defect layer of biological material sandwiched between them. The refractive index of the hemoglobin solution is affected by its concentration, so by changing hemoglobin concentration the propagation of EM waves through 1D-defected PCS is changed.

2. THEORETICAL METHODS

Let’s assume that designed label-free sensor based on defected binary-1D PCs (Figure 1) composed of N-periodic layers of two different materials with different refractive indices and different thicknesses which denoted by n_1,n_2 and d_1 ,d_2 respectively. As well the defect layer is embedded in the middle of structure with refractive index n_D and thickness d_D.

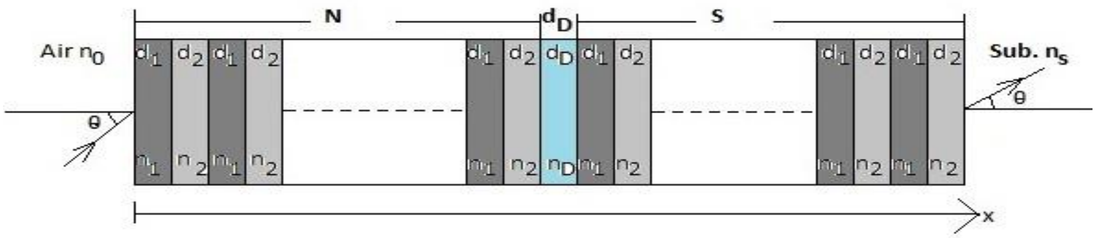

Figure 1 show schematic diagram for 1D defected periodic structure in which the thicknesses of layers that is composed of periodic layers and defect layer are d_1, d_2 and d_D respectively. Also the corresponding refractive indices are n_1, n_2 and n_d respectively. The refractive indices of air and substrate are n_0 and n_s respectively.

The transmission and reflection for propagation of EM waves through binary-1D periodic layered system are calculated by transfer matrix method (TMM) in which the amplitudes of plane waves at different layers are given by [28-31]

$$M = \left(M_A M_B\right)^N M_D \left(M_A M_B\right)^N \tag{1}$$

Where,

$$M_j = \begin{pmatrix} \cos\left(\beta_j\right) & -\dfrac{i}{p_j}\sin\left(\beta_j\right) \\ -i\, p_j \sin\left(\beta_j\right) & \cos\left(\beta_j\right) \end{pmatrix} \tag{2}$$

As, $\beta_j = \dfrac{2\pi d_j}{\lambda} n_j \cos\left(\theta_j\right)$, $p_j = \sqrt{\dfrac{\varepsilon_0}{\mu_0}}\, n_j \cos\left(\theta_j\right)$ for TE mode, each layer *j* has refractive index n_j and thickness d_j. Meanwhile, *j* can be *j* = *A*, *B* and *D*. Then, θ_j is the angle of incident electromagnetic wave with wavelength λ and the transmission coefficient t can be given by:-

$$t = \frac{2 p_0}{\left(M(1,1) + p_f M(1,2)\right) p_0 + \left(M(2,1) + p_f M(2,2)\right)} \tag{3}$$

where, $p_0 = \sqrt{\frac{\varepsilon_0}{\mu_0}} n_0 \cos\theta_0$ and $p_f = \sqrt{\frac{\varepsilon_0}{\mu_0}} n_f \cos\theta_f$.

Finally, the transmittance can be given by:-

$$T = \frac{p_f}{p_0} \left| t^2 \right| \quad (4)$$

In the present structure the defect layer is filled with hemoglobin solution were carried out at PH 7.4, a temperature of 21.5˚c and 100% oxygen saturation. Depending on the refractive indices and therefore dielectric constants for different concentrations of Hb solution, the diffusion of light will vary within photonic crystal periodic structure. For estimating spectrum of the real part of the refractive index for each hemoglobin concentrations between 0 and 29 g/dl we used a model function which formulated by Moritz Friebel and Martina Meinke [32].

$$n_{Hb}(\lambda, C_{Hb}) = n_{H_2O}(\lambda)[\beta(\lambda)C_{Hb} + 1]. \quad (5)$$

This function is valid for wavelength range from 250 to 1100nm. The refractive index of hemoglobin solution n_{Hb} is dependent on wavelength and hemoglobin concentration (C_{Hb}), n_{H_2O} (λ) is the refractive index of water which is dependent on wavelength. The specific refractive increment is β (λ) which is dependent on wavelength and its dependence on the wavelength which is shown in figure 2.

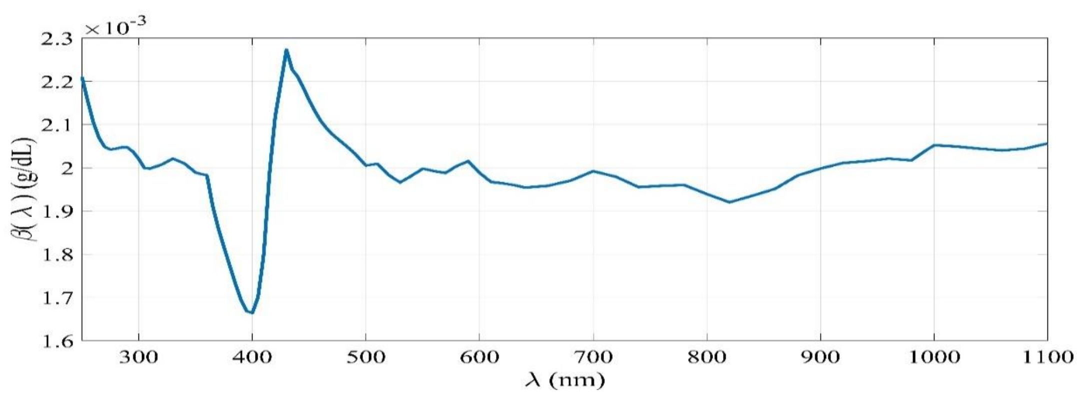

Figure 2 illustrates the specific refractive increment (β) dependent on wavelength range 250nm to 1100nm.

3. RESULTS AND DISCUSSION

Now, we treat the numerical results for the propagations of TE waves through the defective binary-1D PCs through wavelength ranges from 300nm to 1100nm. The present structure is composed of two different dielectric periodic materials which are called Diamond ($n_1 = 2.4168$, $d_1 = 73$ nm) and SiO_2 ($n_2 = 1.46$, $d_2 = 120$ nm) besides embedded the defect layer which is filled with hemoglobin solution. This structure is surrounded by air and SiO_2 substrate with refractive indices are $n_o = 1$ and $n_s = 1.46$ respectively. The transmittance spectrum for our design with Hb solution with concentration of 28.7 g/dL is shown in figure 3.

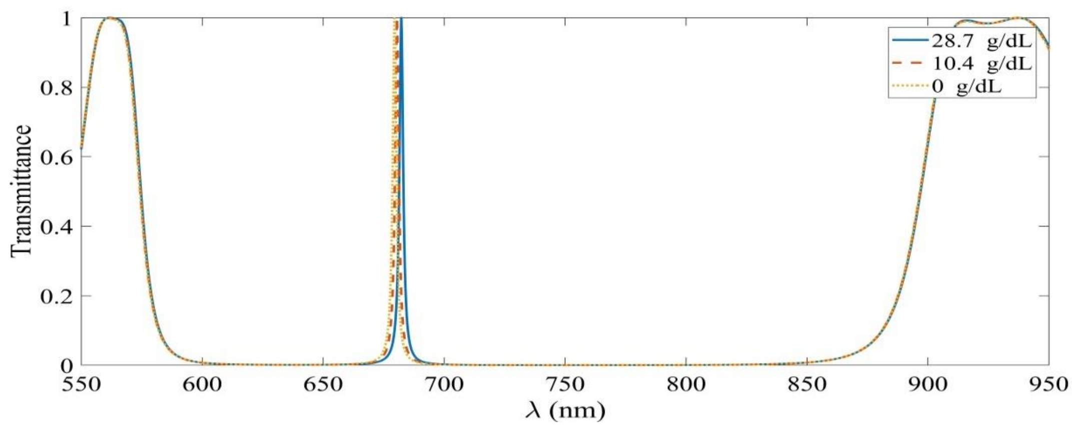

Figure 3 Illustrate the transmission for defected binary-1D photonic crystal for hemoglobin solution with concentrations equal to 0, 10.4, and 28.7 g/dL.

As the results of our calculations, we noticed the creation of photonic band gap (PBG) which is shown in Figure 3 and this PBG appeared founded at the wavelength ranges from 600 nm to near 900 nm. We can explain from Figure 3 that appearance of the defect peak approximately around on 680nm. Therefore, we will focus on transmittance study around this wavelength as shown in Figure 4.

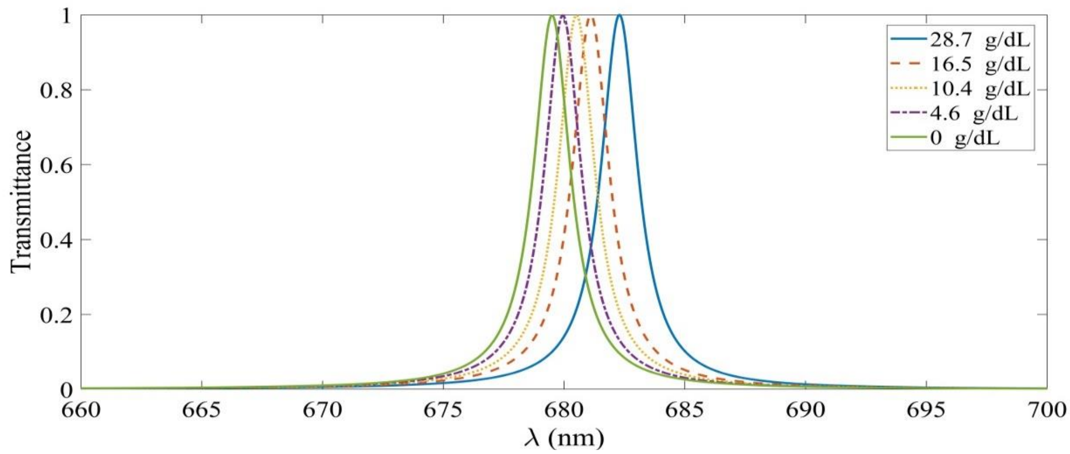

Figure 4 the transmittance spectra for defected binary – 1D PC with defect layer from Hb solution with different concentrations of hemoglobin solution.

The results depicted in figure 4 shows that a shift in the wavelength of defect peak which is observed as the Hb concentrations increases. Where the wavelength of the defect peak are 682.3 nm, 681.1 nm, 680.5 nm, 679.9 nm and 679.5 at hemoglobin concentration 28.7 g/dL 16.5 g/dL, 10.4 g/dL, 4.6 g/dL and 0 g/dL respectively. When the thickness of defect layer is 125 nm, the relation is linear between a wavelength of the defect peak and Hb concentration as shown in figure 5. By using the same design of the present structure, we can obtain the relation between the wavelength of defected peaks in binary-1D PC with the defect layer thicknesses from 110nm up to 140 nm at 28.7 g/dL concentration of Hb solution as shown in figure 6. It is clear that an evident change in the wavelength of the defect peak has a linear relation with the thickness of the defect layer.

The peaks mode appears due to the wave localization inside the defect layer which breaks the structure periodicity. Moreover, the position of this peak mode is located at the central wavelength and could be controlled according to the quarter wavelength. As the defect layer is filled with the glucose solution of concentration, the position of the defect mode is shifted toward the longer wavelength regions as shown in figures. Here, we introduced in different results the sensitivity of the peaks mode characteristics to the variation of the refractive index of glucose solution due to the change of its concentration. The results show that the increase of the refractive index has a pronounced effect on the position of the resonant peak. However, the intensity of the defect mode is unaffected. The present structure could be suitable to act as a sensor for the detection of glucose concentration with high sensitivity and high accuracy. As the defect layer is filled with the glucose solution, the peak is shifted to a new wavelength. In other words, the central wavelength is shifted to a new position due to the variation of the refractive index. Therefore, the value of the refractive index of the glucose solution can be obtained using the quarter wavelength equation.

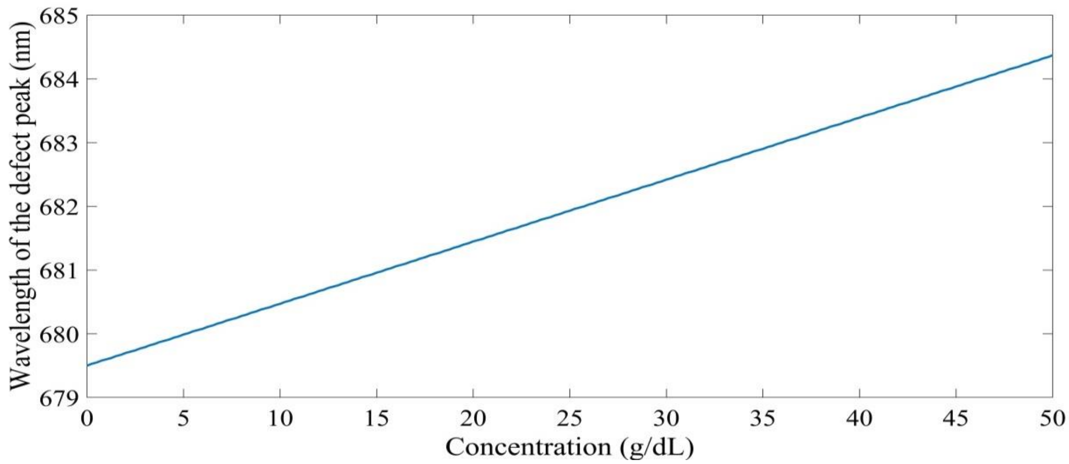

Figure 5 illustrates relation between wavelengths of the defect peaks for defected binary-1D PC with defect layer thickness 125 nm versus concentration of Hb solution.

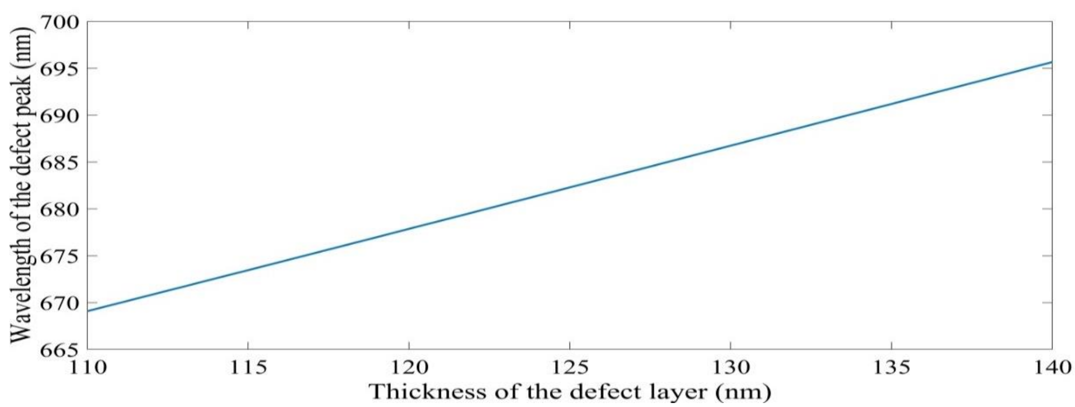

Figure 6 illustrates relation between wavelengths of the defect peaks defected binary-1D PC with defect layer thickness from 110nm up to 140 nm at 28.7 g/dL concentration of Hb solution.

4. CONCLUSIONS

We have investigated the label-free sensor which is based on defected binary -1D photonic crystal air [(Diamond/SiO_2)^N Hb (Diamond/SiO_2)^S] SiO_2. The present calculations are based on transfer matrix method (TMM). The wavelengths of the defect peaks are increased by increasing the hemoglobin concentrations. The peak (half) bandwidth provides important independent information. Bio-substances tend to form a biofilm which would influence peak position. The present work is intent to present and answer an interesting question of light propagation through a 1-dimensional photonic crystal structure, with a localized defect in the form of hemoglobin with different concentrations. The presented idea is simple, and can potentially attract a wider audience when one considers the fact of constantly rising interest of the scientific community (especially biologists and physicians) in the diagnostic methods utilizing different types of the optical phenomena. The proposed design can be used as a label free sensor to determine the hemoglobin concentration in human blood in order to detect anemia and other diseases which is caused by hematological disorders such as leukemia and hemophilia.

References

[1] Light Localisation and Lasing, Edited by Mher Ghulinyan,Lorenzo Pavesi, Publisher Cmbridge University Press,Chp.1, (2014)
[2] E. Yablonovitch, “Inhibited Spontaneous Emission in Solid-State Physics and Electronics”, Phys.Rev.Lett, vol.58, No.20, (1987) 2059
[3] S. John, “Strong Localization of Photons in Certain Disordered Dielectric Superlattices”, Phys.Rev.Lett., Vol.58, No.23, (1987) 2486
[4] A. H. Aly, "Metallic and Superconducting Photonic Crystal", Journal of Superconductivity and Novel Magnetism",Vol. 21,(2008) 421
[5] R. V. Nair, R. Vijaya, “Photonic crystal sensors: An overview”, Progress in Quantum Electronics, Vol. 34, (2010) 89
[6] A. H. Aly, H.-T. Hsu, T.-J. Yang, C.-J. Wu,, and C. K. Hwangbo "Extraordinary optical properties of a superconducting periodic multilayer near zero permittivity operation range", Journal of Applied Physics, Vol.105, (2009) 083917
[7] M. F. Essa, and A. H. Aly, " CR-39 track detector as a photonic crystal" J. Comput. Theor. Nanosci.Vol.6,(2013) 1527
[8] A. H. Aly and D. Mohamed” BSCCO/SrTiO3 One Dimensional Superconducting Photonic Crystal for Many Applications” J Supercond . Nov Magn, Vol.18, (2015) 1699
[9] A. Kumar, V. Kumar, B.Suthar, A.Bhargava, Kh.S.Singh and S.P.Ojha., “Wide Range Temperature Sensors Based on One-Dimensional Photonic crystal with a single Defect”, International Journal of Microwave Science and Technology, Vol.2012, (2012) 1
[10] A.H. Aly and wailed Sayed ” Superconductor-Semiconductor metamaterial photonic crystals” J Supercond Nov Magn, Vol.29, (2016) 1981
[11] A. H Aly, M Essia"Increase in the reflected intensity of X-rays films using photonic crystals " Surface Review and Letters, Vol.24, No. 8,(2017) 1750106
[12] A. H. Aly H. Sayed" Enhancement of the solar cell based on nanophotonic crystals", Journal of Nanophotonics, Vol.11, No.4, (2017) 046020
[13] A. H. Aly, H. Sayed" Computer simulation and modeling of solar energy based on photonic band gap materials" Optica Applicata , Vol.48,No.s.1, (2018) 117

[14] A. H. Aly, A. A. Ameen and D.Vigneswaram "Superconductor Nanometallic Photonic Crystals as a Novel Smart Window for Low-Temperature Applications" J Supercond Nov Magn.,Vol.32, Iss,2, (2019) 191
[15] A. H. Aly, S.E.-S. Abd El-Ghany and B M Kamal, “study the filtering process in one dimensional photonic crystal with and without defect semiconductors”, International Journal of Advances in Engineering &Technology, Vol. 8, No.2, (2015) 59
[16] A H. Aly, S. E. –S. Abd El-Ghany, M. M. Fadallah, F. E. Salman, and B. M. Kamal, “Transmission and Temperature Sensing Characteristics of a Binary and Ternary Photonic Band Gap”, journal of Nanoelectronics and optoelectronics, Vol.10, No.1, (2015) 1
[17] S.E-S. Abd El-Ghany,” Temperature Sensors Based on One Dimensional Photonic Crystals with different Double Defects”, Journal of Nanoelectronics and Optoelectronics, Vol.13, No.2, (2018) 221
[18] S. Surdo, S. Merlo, F. Carpignano, L. M. Strambini, C,Trono, A. Giannetti, F. Baldini and G. Barillaro, “ Optofluidic microsystems with integrated vertical one-dimensional photonic crystals for chemical analysis”, Dynamic Article links , Vol. 12 (2012) 4403
[19] G. Barillaro, S. Merlo, S. Surdo, L.M. Strambini, F. Carpignano “Integrated optofluidic microsystem based on vertical high-order one-dimensional silicon photonic crystals”, Microfluid Nanofluid, Vol. 12, (2012) 545
[20] U. ERDIVEN ,M .KARAASLAN ,E .UNAL AND F .KARADAG , “Planar Photonic Crystals Biosensor Applications of TiO_2”, ACTA PHYSICA POLONICA A, Vol. 122, No.4, (2012) 732
[21] S. Surdo, F. Carpignano, L.M. Strambini, S.Merlo and G.Barillaro, “Capillarity – driven (self-powered) one-dimensional photonic crystals for refractometry and (bio) sensing applications”,royal society of chemistry, Vol.4, (2014) 51935
[22] M.Mohebbi,” Refractive index sensing of gases based on a one-dimensional photonic crystal nanocavity”, Journal of Sensors and Sensor System, Vol.4, (2015) 209
[23] J. Wang,” Survey and summary from DNA biosensors to gene chips”, Nucleic Acids Research, Vol.28, No.16, (2000) 3011
[24] N. I. Grigorchuk "Sensitivity of surface plasmon resonances in spheroidal metal nanoparticles" Eur. Phys. J. B 84 (2014) 252
[25] I.S. Amiri ,Bikash Kumar Paul, Kawsar Ahmed, Arafa H Aly, R Zakaria, P Yupapin, D Vigneswaran, "Tri-core photonic crystal fiber based refractive index dual sensor for salinity and temperature detection, Microwave and Optical Technology Letters, Vol. 61, No. 3 (2019) 847
[26] H. Chopra, Rajinder S. Kaler, and Balveer Painam, “Photonic crystal waveguide-based biosensor for detection of diseases”, J. Nanophotonics, Vol.10, No.3, (2016) 03611-1 – 03611
[27] P. Sharma, P. Deshmukh and P. Sharan, “Desin and analysis of blood comonents by using optical sensors”, Int. J. of Curr.Resear., Vol. No.. 08, (2013) 2225
[28] A. H. Aly " Electromagnetic wave propagation characteristics in one-dimensional photonic crystals" in Handbook of Wave Propagation in Materials for Modern Applications: Edited by Andrey Petrinm, Chapter 10, Publisher: Sciyo, (2010) 193
[29] A. H Aly and S.-W. Ryu " Study of optical transmission in nanometallic photonic crystal", J. Comput. Theor. Nanosci. Vol.5, No.10, (2008) 597
[30] A. H. Aly , S.-W. Ryu and C.-J. Wu “Electromagnetic wave propagation characteristics in one-dimensional metallic photonic crystals", Journal of Nonlinear Optical Physics, Materials (JNOPM), Vol.17, No.3, (2008) 255

Exp. Theo. NANOTECHNOLOGY 3 (2019) 437-446

[31] A. H. Aly, "Metallic and Superconducting Photonic Crystal", Journal of Superconductivity and Novel Magnetism",Vol. 21, No.10, (2008) 421
[32] Rida Ahmed Ammar, Exp. Theo. NANOTECHNOLOGY 2 (2018) 1