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Recent Progress of Photonic Crystal for Bio-sensing Application

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Abstract. New-fangled applications of photonic crystal structure are reviewed in this paper. Different type's bio-sensing mechanism using 2D and 3D photonics crystal is envisaged with help of powerful numerical technique. Present review research divulged a novel technique to investigate the components of biomaterial using plane wave expansion method. The principle of investigation of bio-components is based on linear variation of photonic band gap of crystal structure pertaining to the amount of bio-elements

Keywords: Photonic crystal, plane wave expansion method, photonic band gap, Bio-materials

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1. Introduction

Though the research on photonic is at an infant stage, recently photonic crystal is mounted up focusing owing to its exotic properties and applications. So far as past of photonic crystal is concerned, researchers were not realizing till 1988. However two mile stone paper by E. Yablonovitch and S. Jhon bring new light to photonic technology [1,2]. Since then, research on photonic crystal has been burgeoning time to time and it provides useful information and application to society. Moreover, the extension of photonic crystal has already penetrated into matamaterial research [3,4]. Even though work on optical crystal is stepping forward, it is not growing fast owing to fabrication feasibility which play vital role to explore real application. The fabrication feasibility is getting withstand because of hard to trapping of photon particles. Based on current research scenario, one dimensional photonic crystal has reached at mature stage pertaining to fabrication and application. But even though some works have been done using two dimensional crystal structure, it is at young stage so far. However three dimensional photonic crystal structure is still at infant stage owing to constrain of fabrication. As far application of photonic crystal structure is concerned, manifold application are found now-a- days using same type of structures. Out of which, sensing application using 2D and 3D pictures are lucidly presented in this paper. For example; here we deal with 2D photonic structures for investigation of concentration of sugar, salt, alcohol , cygel , and potassium chloride in their aqueous solution and hydrogel in PAM hydogel solution[5-8], where 3D photonic crystal deals with blood-hemoglobin-glycerol solution [9].

This paper is prearranged as follows; Section 2 establishes a necessary mathematical treatment to find out the photonic band gap of 2D and 3D photonic crystal structure, where section 3 proposes an experimental set up to obtain the concentration. Section 4 discusses the result and interpretation of transmitted intensities .Finally conclusion is dealt with section 5.

2. Mathematical treatment

As far as computational techniques for bio-sensing application is concerned, we use plane wave expansion method to investigate the concentration of biomaterials using 2 and 3 D photonic crystal structure. Moreover photonic band gap analysis is key a parameter for the same investigation. Again to realize the photonic bandgap , we make a simple mathematical analysis of plane wave expansion method with regard to 2 and 3D photonic crystal [10].

2.1 Mathematical approach for 2 D photonic crystal structure

In this investigation, the light propagation in 2 D photonic crystal along Z axis and radiation has TE, polarization (Non zero H_z , E_x ,E_y,), Helmoltz equation for such a radiation field can be obtained from Maxwell's equations as

$$-\{\frac{\partial}{\partial x}\frac{1}{\in(r_{\|})}\frac{\partial}{\partial x}+\frac{\partial}{\partial y}\frac{1}{\in(r_{\|})}\frac{\partial}{\partial y}\}H_z(r_{\|})=\frac{\supset^2}{c^2}H_z(r_{\|}) \tag{1}$$

Here $r_{\|}$ is 2D vector in xy plane.

The wave functions are represented in terms of Bloch waves and expanded into Fourier's series over the lattice vectors. Inversed dielectric constant is also expanded into Fourier series. Substituting this in equation (1) , the eigen value for Fourier expansion coefficient is obtained as

$$\sum_{G_{||}} \frown(G_{||} - G'_{||})\,|\,K_{||} + G'_{||}\,|^{2} E_{z,K_{||},n}(G'_{||}) = \frac{\supset_{K_{||}n}^{(E)^{2}}}{c^{2}} E_{z,K_{||}n}(G_{||}) \qquad (2)$$

Where $G_{||}$ and $G'_{||}$ are in plane reciprocal lattice vector.

$K_{||}$ is in plane vector and $\omega^{(E)}{}_{K_{||},n}$ is the frequency of TM mode.

$\chi(G_{||})$ for dielectric rods can be expressed as

$$\frown(G_{||}) = 2f\left(\frac{1}{\in_1} - \frac{1}{\in_2}\right)\frac{J_1(G_{r||})}{G_{r||}} \qquad (3)$$

where $J_1(G_{r||})$ is the first order of Bessel's function.

For simulation we compute the photonic band gap using equation (3) and limit the variation of Brillioun zone $\frac{-\pi}{T}$ …….. $\frac{\pi}{T}$, G and G' within $\frac{-2\pi N}{T}$ …. $\frac{2\pi N}{T}$, where (2N+1) is the number of plane waves taken into account

Using equation (2), we write down the matrix differential operator for each values of wave vector within the selected range and the eigen states of obtained matrix is computed

2.2 Mathematical approach for 3 D photonic crystal structure

3D photonic crystal structure possess periodically in three directions and their band structure computations are made using Helmholtz equations, which is given by

$$\frac{1}{\in(r)} \nabla \times \{\nabla \times \mathrm{E(r)}\} = \frac{\omega^2}{\mathrm{c}^2}\,\mathrm{E(r)} \qquad (4)$$

Where 'r' is a 3D vector in coordinate system.

To search the Eigen state of infinite periodic structure, spatial distributions of electric field components is represented in the form of Bloch functions. Then the plane wave multiplied by periodic functions with the periodicity of lattice, i.e.

$$E(r) = E_{k,n}(r)e^{ik.r} \qquad (5)$$

where $E_{k,n}$ are the periodic functions with periodicity of lattice.

Since the function is periodic, it satisfies the following condition;

$$E_{k,n}(r) = E_{k,n}(r + R) \tag{6}$$

Where R is the lattice vector

The periodicity of wave function in equation (6) leads to possibilities of their Fourier expansion over reciprocal lattice vector.

So wave function in the wave vectors space is represented as

$$E_{k,n}(r) = \sum_G E'_{k,n}\,(G)\, e^{i(k+G).r} \tag{7}$$

Where, G is the reciprocal lattice vector.

Taking above concept, the dielectric function is also expanded to the Fourier series as

$$\frac{1}{\epsilon(r)} = \sum_G \chi\,(G)\, e^{i\,G.r} \tag{8}$$

Where, χ (G) is Fourier expansion coefficient, which depends on the reciprocal lattice vector.

Substituting equation (7) and (8) in to equation (4) and after simplification, we obtained Eigen-value equations for Fourier expansion coefficient of electric field, which is given by

$$-\sum_{G'} \chi(G\text{-}G').(k + G') \times (k + G') \times E'_{k,n}\,(G)$$
$$= \sum_G E'_{k,n}\,(G)\, e^{i(k+G).r} \tag{9}$$

Using equation (9), different wave vectors of 3D band structures are computed.

3. Proposed experimental structure set up

Though this paper deals with theoretical investigation, an experimental setup is divulged here to measure the different bio-components in their respective solutions. The proposed experimental set up is shown in figure 1

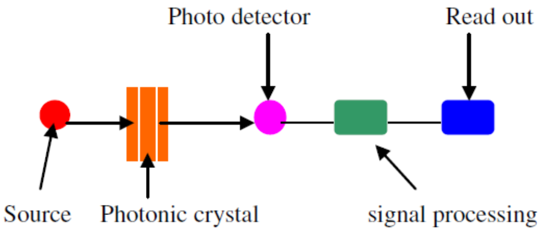

Fig. 1. Experimental setup for biosensing application

In figure 1, electromagnetic source emanates a signal with particular wavelength incident on crystal structure then signal at a particular range of wavelength are reflected back which is nothing but the photonic bandgap. The rest amount of transmitted signal reaches at detector which converts to equivalent potential corresponding to transmitted signal at each concentration of bio-component. We use 589 nm wavelengths as input signal for 2D photonic crystal structure where 540 nm wavelengths is used for 3 D photonic crystal structure. Though the above proposed set up explains different components to measure the bio-elements, this paper focuses on photonic crystal structure only. To understand the same, figure 2(a) and 2(b) representstwo and three dimensions photonic crystal structure respectively.

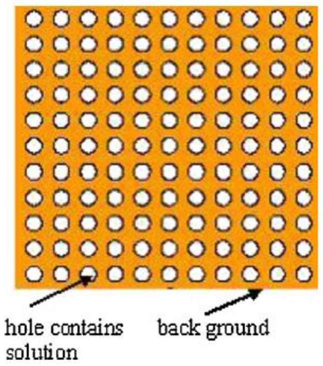

Fig. 2(a). 2D photonic crystal structure with silicon as background materials.

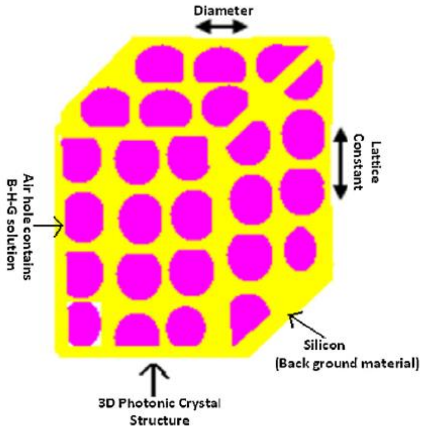

Fig. 2(b). 2D photonic crystal structure with silicon as background materials

Figure 2(a) and 2(b) represents two and three dimensions photonic crystal structure with silicon as background material. The lattice spacing of structure is taken of 1 μm for both the cases , however diameter of air holes is not same for all cases. For example diameter of air holes is taken of 0.8 μm. and 0.88 μm for 2D and 3D structure respectively. The reason for choosing such parameters is that sensing application can be realized at aforementioned parameters. Apart from this, these works deal with silicon as background material owing to compatible with photonic devices.

4. Result and discussion

In essence the review paper deals with 2 and 3 dimensional photonic crystal structure for finding different bio-components in their aqueous solution. In particular, the measurement of concentration of sugar, salt, alcohol cygel^{TM} , potassium chloride in their aqueous and sucrose in its PAM hydogel is made using 2D photonic crystal structure., where measurement of glycerol concentration in B-H-G solution is made using 3D photonic crystal structure.

4.1 Sensing application using 2D photonic crystal structure

As far as 2D photonic crystal structure is concerned, figure 2(a) deals with the aqueous solution of alcohol , cygel^{TM}, potassium chloride and sucrose solution. To compute above bio-elements, signal 589 nm manipulates with 2D photonic crystal structure with different percentage of biomaterial then light having particular range of frequency gets reflected. The range of frequencies are realized by photonic band gap analysis.Consisting of above concept the photonic band gap 2D photonic crystal structure for 7.5 % of sugar solution in their sensing, 10% of sucrose solution of PAM hydrogel, 85 % , cygel^{TM} in their equations are shown in figure 3(a) (b) and (c) respectively. Other results are done but not shown here.

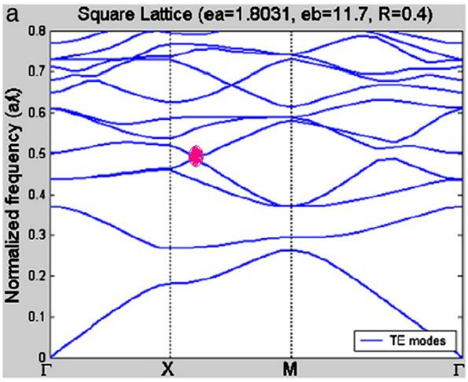

Fig. 3(a) ; Photonic band gap for 7.5 % of sugar in their aqueous

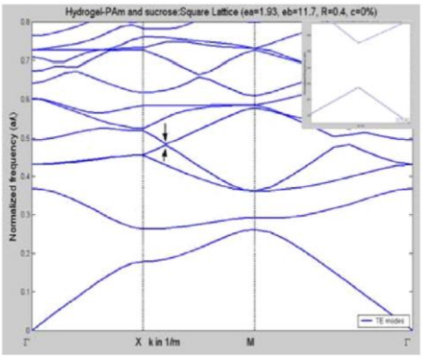

Fig. 3(b). Photonic band gap for 10 % of sucrose in PAM hydrogel

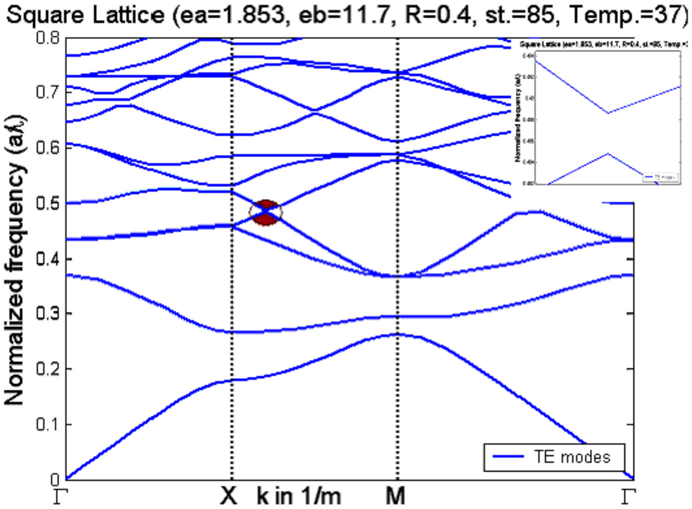

Fig. 3(c). Photonic band gap for 85% of Cygel^{TM} in their aqueous

In these figure normalized frequency is taken along vertical axis with propagation vector in m^{-1} is taken as horizontal axis. Here photonic band gap of above said structure is easily envisaged in diagrams which is mentioned in circular mark and the complete photonic bandgap in this figures represent the reflected signal. Further moving to computation of transmitted signal corresponding each concentration, it is realized that the difference of input signal and photonic band gap represents transmitted signal. With consideration of above technique, the variation of transmitted signal with different concentration in 2D pictures are shown 3 (d), (e) and (f) for sugar, potassium chloride and hydrogel respectively

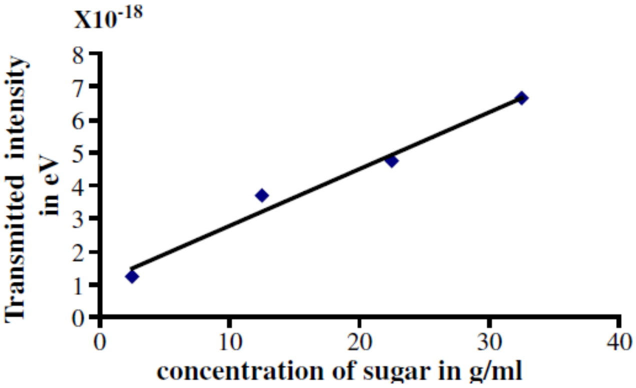

Fig.3(d). Transmitted intensity for sugar in their aqueous

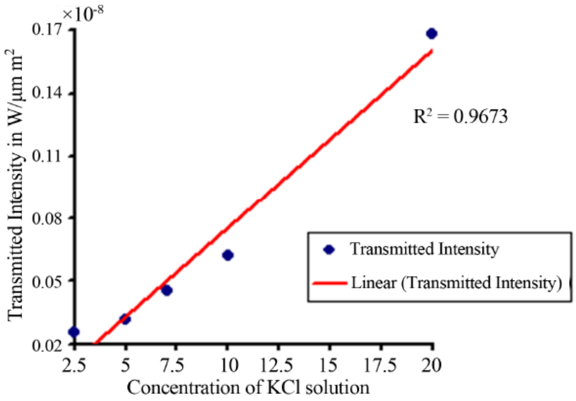

Fig. 3(e). Transmitted intensity for potassium chloride in their aqueous

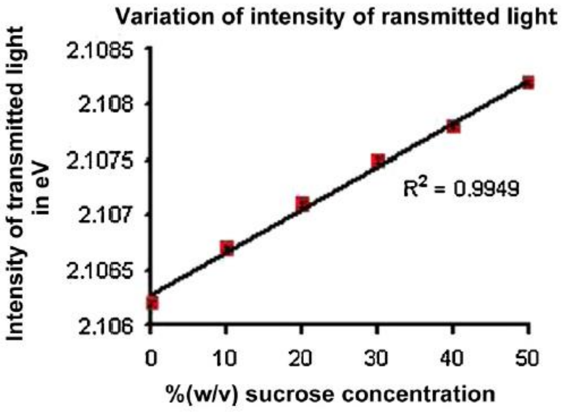

Fig. 3(f). Transmitted intensity for sucrose in PAM hydrogel

From above figure it is seen that intensity transmitted through photonic crystal structure is taken along vertical axis and concentration of different bio-elements is taken along horizontal axis. In all cases, the variation of transmitted intensity is found linear, which leads to an accurate measurement of above mentioned bio-elements using 2D photonic crystal structure.

4.2 Sensing application using 3D photonic crystal structure

Extending above work to 3D photonic structure, this paper investigates the concentration of glycerol in blood-hemoglobin -glycerol solution. The estimation of glycerol is made using figure 1 and 2(b). The electromagnetic wave with wavelength 540 nm is incident on 3D photonic crystal structure, and then reflected light is measured with the help of complete photonic band gap of 3D photonic crystal structure. Further, intensity emerging from 3D photonic crystal is collected as photodetector and finally reaches at output end. Moreover, the intensity of emerging at the end is obtained for each concentration of glycerol in B-H-G solution. The simulation result for transmitted intensity is plotted in figure 4(b).

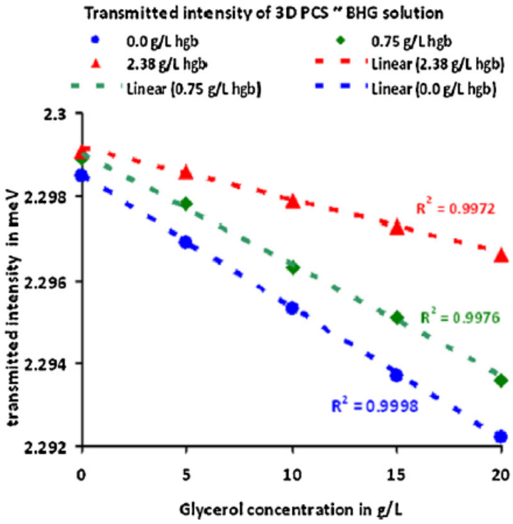

Fig. 4. Transmitted intensity for glycerol in their aqueous

Here transmitted intensity in µw/m^2 is taken along y axis with respect to concentration of glycerol in x axis. An excellent result corresponding to each concentration are found .For example; variation of transmitted intensity pertaining to concentration of glycerol show a beautiful linearship ($R^2 > 0.99$), which leads an accurate investigation of glycerol in B-H-G solutions.

5. Conclusion

Techniques for measurement of concentration of sugar, salt, alcohol, potassium chloride, cygel^{TM}, sucrose ,and glycerol are presented using both two dimensional and three dimensional photonic crystal structure. Photonic bandgap is the intrinsic parameters to realize the computation of above said bio-components in their aqueous solutions. The wavelength 589 nm for 2D and 540 nm for 3D is used to investigate the intensity emerging from photonic crystal structure. Simulation result divulged that an excellent variation of transmitted intensity leads an accurate measurement of bio-components. Lastly, present article ensures that 2D and 3D photonic crystal structure may be a good candidate for bio-sensing application.

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