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Measurement of glycerol concentration in B–H–G solution using 3D photonic crystal structure

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ABSTRACT

A novel technique is used to measure the concentration of glycerol in blood-hemoglobin-glycerol (B–H–G) solution using 3D photonic crystal structure is presented in this paper. Glycerol concentration is estimated accurately by measuring the intensities of transmitted light. Here, reflection as well as absorption losses is considered to measure the transmitted intensity of light having wavelength 540 nm. The principle of measurement is based on the linear variation of photonic band gap with respect to glycerol concentration. Simulations for photonic band gap are made using plane wave expansion (PWE) method. An experimental set up is theoretically designed to measure the concentration of glycerol at different hemoglobin concentration.

1. Introduction

In last decades, photonic crystals have been received extensive studies owing to their academic and practical interests .The physics of photonic crystals is conventionally described in similar form to the solid state physics of electronic materials, where scattering of light wave takes place from the periodic variations in the dielectric constants [1,2]. The dispersion relation or band structure is used to analyze the wave properties of crystal structure. This dispersion relation determines the photonic band gaps is complete or pseudo. Complete photonic band gap allows a strong localization of light in all directions [3]. Photonic crystal can be realized by drilling air holes on the background materials. Taking this concept, one can construct 1D, 2D and 3D photonic crystal structure. As far as the fabrication is concerned, 1D photonic crystal is fabricated easily than 2D and 3D photonic crystal structures. So the commercial applications of 1D photonic crystal structure have been entered fully in to the market [4,5]. Although 2D photonic crystal technology is not attained mature stage so far, people have designed 2D photonic crystal structures successfully for the sake of commercial applications [6].

Similarly, though a 3D photonic crystals are in an infant stage, they can be fabricated using a variety of advanced SiMEMS (micro electro mechanical systems) and IC (integrated circuits) process[7].

As far as sensing applications using photonic crystal structure is concerned, recently the concentrations of sugar, salt, alcohol and cygel are measured using photonic crystal structure [8,9]. In this case measurement is done using 2D photonic crystal structure, but here for the first time, we are dealing with a novel technique, which is used to measure the glycerol concentration in blood-hemoglobin-glycerol (B–H–G) solutions using 3D photonic crystal structure.

The photonic crystal structure, which is used to measure the concentration of glycerol at different amount of hemoglobin in B–H–G solution, is shown in Fig. 1.

The aforesaid figure represents a 3D photonic crystal structure having silicon as background material. It is seen that air holes are distributed throughout the crystal structure in periodic manner. The lattice constant of the structure and diameter of the air holes are 1 μm and 0.88 μm respectively. To estimate the glycerol concentration, B–H–G solutions having different glycerol concentration at different hemoglobin are infiltrated in to air holes.

Photonic band gap of 3D silicon crystal structure having different concentration of B–H–G solutions are obtained using plane wave expansion (PWE) method. After obtaining photonic band gaps, reflection losses are determined. Apart from reflection loss (reflectance), absorption loss is also included to find out the transmitted intensity of light through this photonic crystal structure. In this case two types of absorption losses are considered such as absorption loss due to silicon material and absorption loss due to B–H–G solution at different concentration of glycerol and hemoglobin.

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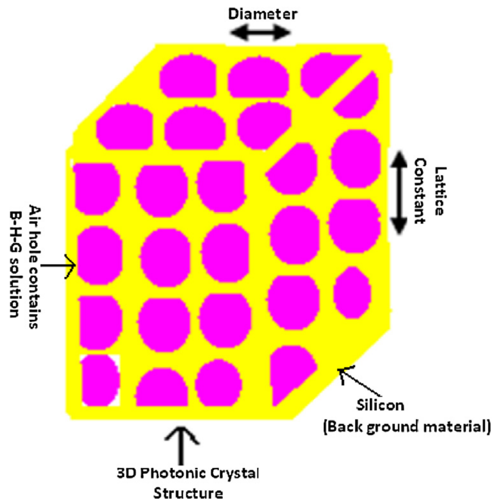

Fig. 1. Schematic diagram of 3D photonic crystal structure.

Although each component in the blood plays an important role, the addition of glycerol in blood give ample benefits in the field of medical science.

The preservation of red blood cells (RBCs) with glycerol, an intracellular cryoprotective agent, is routinely used by canadian blood services (CBS) and other blood manufacturers in order to maintain an inventory of donor units with rare phenotypes. RBCs cryopreserved with glycerol are also important for military deployment and help toensure that an adequate blood supply is available in situations where demand is uncertain [10]. Rapid dilution of RBCs containing a high intracellular glycerol concentration into isotonic solutions will result in hemolysis. Once thawed, RBCs cryopreserved in glycerol must be processed to remove the intracellular cryoprotectant so that hemolysis during in vitro compatibility testing and intravascular hemolysis upon transfusion is prevented [11]. This is accomplished by washing the RBCs with decreasing concentrations of a saline solution to osmotically remove the intracellular glycerol. Washing also has the additional benefit of removing free hemoglobin, potassium and/or protein from the supernatant.

This paper is organized as follows; section 2 presents the mathematical approach of PWE technique for 3D photonic crystal structure. Photonic band analysis is discussed in section 3. Absorption decay factor of photonic crystal structure is discussed in section 4. Finally conclusions are drawn in section 5.

2. Mathematical approach

3D photonic crystal structure possess periodically in three directions and their band structure computations are made using Helmholtz equations, which is given by [12]

$$\frac{1}{\varepsilon(r)}\nabla\times\{\nabla\times E(r)\}=\frac{\omega^2}{c^2}E(r) \quad (1)$$

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.,

$$E(r)=E_{k,n}(r)e^{ik,r} \quad (2)$$

where $E_{k,n}$ are the periodic functions with periodicity of lattice.Since the function is periodic, it satisfies the following condition;

$$E_{k,n}(r)=E_{k,n}(r+R) \quad (3)$$

Table 1
Variation of refractive indices of B–H–G solutions with glycerol concentration at different hemoglobin concentration.

Glycerol concentration in (g/L)	Refractive index of B–H–G solution		
	H = 0.0 g/L hgb	H = 0.75 g/L hgb	H = 2.38 g/L hgb
0	18.5	19.9	24.1
5	20.6	22.7	29.7
10	23.4	31.8	36
15	36	38.1	40.9
20	41.6	43.7	47.9

where *R* is the lattice vector

The periodicity of wave function in Eq. (2) leads to possibilities of their Fourier expansion over reciprocal lattice vector. So wave function in the wave vectors space is represented as

$$E_{k,n}(r)=\sum\nolimits_G E'_{k,n}(G)e^{i(k+G)r} \quad (4)$$

where, *G* is the reciprocal lattice vector.

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

$$\frac{1}{\varepsilon(r)}=\sum\nolimits_G \chi(G)e^{iG,r} \quad (5)$$

where, $\chi(G)$ is Fourier expansion coefficient, which depends on the reciprocal lattice vector.

Substituting Eq. (4) and (5) in to Eq. (1) and after simplification, we obtained Eigen-value equations for Fourier expansion coefficient of electric field, which is given by $\sum_G \chi(G-G')\times(k+G')\times(k+G')\times E'_{k,n}(G)$

$$\sum\nolimits_G E'_{k,n}(G)e^{i(k+G)\times r} \quad (6)$$

Using Eq. (6), different wave vectors of 3D band structures are computed.

3. Photonic bandgap analysis

To investigate the glycerol concentration in B–H–G solutions, simulations are made to obtain photonic band gap using suitable structure parameters of crystal. Here, 3D photonic crystal structure is realized by drilling air holes on silicon crystal, which is treated as background material. Then the mingling of blood, hemoglobin and glycerol solutions is infiltrated in the air holes. As far as structure parameters are concerned, the lattice constant of 1 μm and the diameter of air holes of 0.88 μm taken. Apart from these, refractive indices of B–H–G solution are considered with respect to different concentrations (g/L) of glycerol and hemoglobin. The same data is shown in Table 1 [13].

Considering aforementioned parameters' of silicon photonic crystal structure (discussed in introduction section) and using data from Table 1, simulation is done using plane wave expansion method to find out the photonic band gap of 3D photonic crystal structure, which contains B–H–G solution having different quantities (g/L) of glycerol concentrations. The simulation results for 0.0 g/L,0.75 g/L, 2.38 g/L concentration of hemoglobin are shown in Figs. 2–4a and b respectively. Other simulations are done but not shown here.

Fig. 2a and b represent dispersion diagram for 0.0 g/L and 20.0 g/L concentration of glycerol at 0.0 g/L concentration of hemoglobin in B–H–G solution. And Fig. 3a and b represent dispersion diagram for 0.0 g/L and 20.0 g/L concentration of glycerol at 0.75 g/L concentration of hemoglobin in B–H–G solution. Similarly, Fig. 4a and b represent dispersion diagram for 0.0 g/L and 20.0 g/L concentration of glycerol at 2.38 g/L concentration of hemoglobin in B–H–G solution.