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Theoretical model for measurement of hemoglobin in human blood using 3D photonic crystal structure

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ABSTRACT

Because the concentration of hemoglobin in the human blood is important, optical measurement using 3D photonic crystal structure is presented in this structure. Here the concentration of oxygenated and deoxygenated hemoglobin in human blood is determined for two different wavelengths of 589 nm and 633 nm. The principle of measurement is based on the linear variation of photonic band gap with respect to concentration of both oxygenated and deoxygenated hemoglobin. The simulations for photonic band gap of 3D photonic crystal structure having different concentrations of hemoglobin are determined using plane wave expansion method. Again, simulation is also done to find out the absorption loss due to both silicon crystal structure and hemoglobin with respect to different concentration of hemoglobin in blood. An experimental set up is designed to measure the transmitted intensity with respect to these concentration of hemoglobin in the blood.

1. Introduction

Photonic crystals have been the subject of considerable research in recent years owing to their attractive applications. Basically photonic crystals are dielectric structures having periodically modulated index of refraction [1]. These crystals are artificial dielectrics or metals periodic structure in one, two or three dimensions that forbid light propagation at certain frequency called as photonic band gap. Although one and two dimensional photonic crystal structures control the light guiding, the three dimensional photonic crystal structures provides complete control the guiding of light [2]. As far as medical application using photonic crystal structure is concerned, the measurement of concentration of sugar, salt and alcohol is done using 2D photonic crystal structure [3]. Again using similar type of structure, the strength of Cygel is also determined [4]. Apart from these, recently a 2D silicon photonic structure is used to estimate the concentration of sucrose in PAm hydrogel [5]. But here for the first time we deal with a 3D photonic crystal structure having silicon as background material which determines the concentration of oxygenated and deoxygenated hemoglobin in the human blood at visible range, wavelength of 589 nm and 633 nm.

Blood optics is an important for biophotonic and clinical applications both in theory and diagnosis [6]. Hemoglobin in the blood plays vital role for the sake of blood circulation through human vein [7]. In blood, hemoglobin is present both in the oxygenated and deoxygenated forms and therefore, both forms are studied here.

In this paper, we have measured the concentration of oxygenated and deoxygenated hemoglobin in human blood using 3D photonic crystal structure, which is shown in Fig. 1.

Fig. 1 represents three-dimensional (3D) photonic crystal structure having silicon as background material. It is seen that air holes are distributed throughout the crystal structure (along three directions) in periodic manner. The lattice constant of the structure and diameter of the air holes are 1 μm and 432 nm, respectively. To estimate the hemoglobin concentration in human blood, blood solutions are infiltrated in to air holes.

This paper is organized as follows: In Section 2, principle of measurement is presented. Photonic band gaps of 3D photonic crystal structure are analyzed in Section 3. In Section 4, absorption decay factor is discussed. Experimental set up is designed in Section 5. Finally, conclusions are drawn in Section 6.

2. Principle of measurement

The principle of measurement is based on the linear variation of photonic band gap with respect to concentration of oxygenated and deoxygenated hemoglobin at wavelength 589 nm and 633 nm. These photonic band gaps of 3D photonic crystal structure are obtained using plane wave expansion method. After finding photonic band gap of said structure, the reflectance is obtained for each

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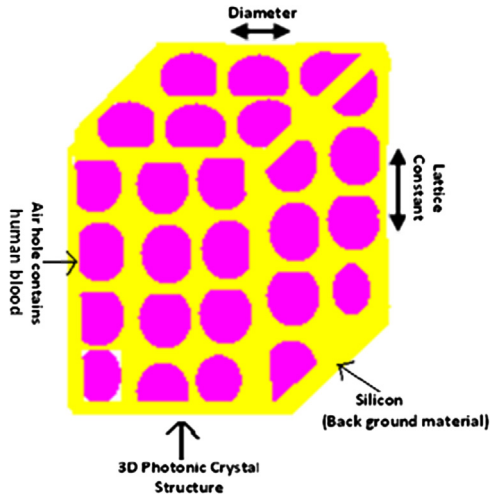

Fig. 1. Schematic diagram of 3D photonic crystal structure.

concentrations of oxygenated and deoxygenated hemoglobin in the human blood. Simulations are also made to find out the absorption of the same structure at wavelength 589 nm and 633 nm. The combination of photonic band gap (reflectance) and absorption, is nothing but energy loss by the 3D photonic crystal structure having blood at different percentage of hemoglobin concentration. Finally, transmitted intensity of light corresponding to each concentration of hemoglobin is obtained. Knowing the amount of intensities of transmitted light, the concentration of hemoglobin in the blood is estimated.

3. Photonic band gap analysis

To investigate the hemoglobin concentration in human blood solutions, simulations are made using suitable parameters of 3D photonic crystal structure. Here, 3D photonic crystal structure is realized by drilling air holes on silicon crystal, which is treated as background material. Then blood having oxygenated and deoxygenated hemoglobin are infiltrated in the air holes. As far as input parameters are concerned, the lattice constant of 1 μm and the diameter of air holes of 432 nm taken. Apart from these, refractive indices of human blood are taken with respect to different percentages (g/L) of deoxygenated (DOXY) and oxygenated (OXY) hemoglobin concentration at different wavelengths (589 nm and 633 nm). The same data is shown in Table 1 [8].

Choosing structure parameters 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 human blood having different quantities (g/L) of hemoglobin concentrations.

The simulation results for deoxygenated hemoglobin of 0 g/L and 140 g/L concentration at 589 and 633 nm are shown in Fig. 2(a)–(d). Similarly simulation results for oxygenated hemoglobin of 0 g/L and 140 g/L concentration at 589 and 633 nm are shown in Fig. 3(a)–(d). Other simulations are made but not shown here

Fig. 2(a) and (b) represents dispersion diagram for 0.0 g/L and 140.0 g/L concentration of deoxygenated hemoglobin in human blood at wavelength of 590 nm and Fig. 2(c) and (d) represents dispersion diagram for 0.0 g/L and 140.0 g/L concentration of deoxygenated hemoglobin in human blood at wavelength of 633 nm. Similarly, Fig. 3(a) and (b) represents dispersion diagram for 0.0 g/L and 140.0 g/L concentration of oxygenated hemoglobin in human blood at wavelength of 590 nm and Fig. 3(c) and (d) represents

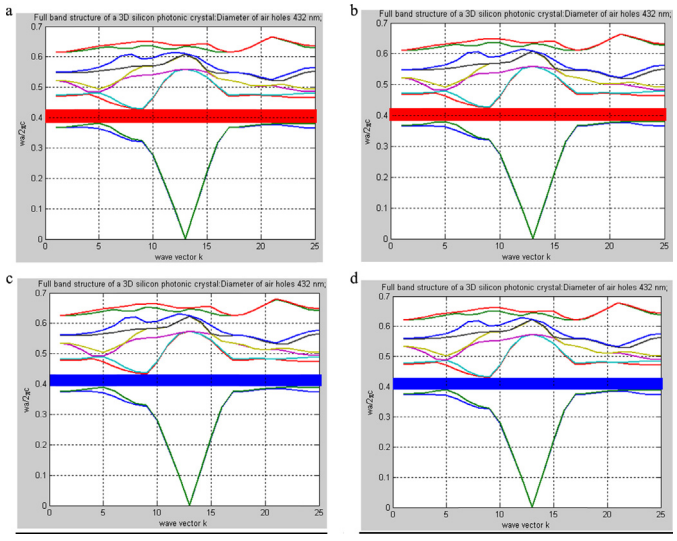

Fig. 2 (. a) Simulated dispersion diagram for deoxygenated hemoglobin of 0 g/L concentration at 589 nm. (b) Simulated dispersion diagram for deoxygenated hemoglobin of 140.0 g/L concentration at 589 nm. (c) Simulated dispersion diagram for deoxygenated hemoglobin of 0 g/L concentration at 633 nm. (d) Simulated dispersion diagram for deoxygenated hemoglobin of 140 g/L concentration at 633 nm.

dispersion diagram for 0.0 g/L and 140.0 g/L concentration of oxygenated hemoglobin in human blood at wavelength of 633 nm.

In these above diagrams, wave vector in m^{-1} is taken along *x*-axis, where normalized frequency is taken along *y*-axis. It is also seen that, photonic band gap is represented corresponding to each band (blue, red, pink and green color) shown in each simulated dispersion diagram. Then the width of the color line is nothing but the values of normalized frequency. And photonic band gap is calculated for each normalized frequency.

It is evident from Fig. 2(a) and (b) that, at 589 nm wavelength, photonic band gap decreases from 56.26 meV to 54.20 with respect to deoxygenated hemoglobin concentration, which varies from 0.0 to 140.0 g/L. And at 633 nm wavelength, photonic band gap decreases from 54.37 meV to 52.29 meVwith respect to deoxygenated hemoglobin concentration, which varies from 0.0 to 140.0 g/L.

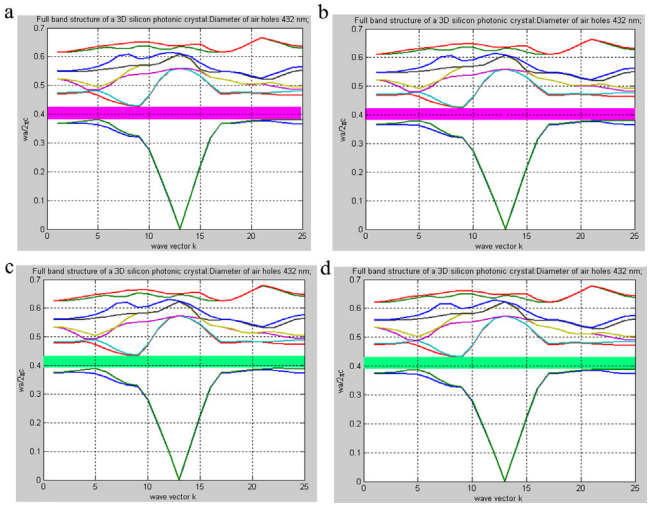

Fig. 3. (a) Simulated dispersion diagram for oxygenated hemoglobin of 0 g/L concentration at 589 nm. (b) Simulated dispersion diagram for oxygenated hemoglobin of 140 g/L concentration at 589 nm. (c) Simulated dispersion diagram for oxygenated hemoglobin of 0 g/L concentration at 633 nm. (d) Simulated dispersion diagram for oxygenated hemoglobin of 140 g/L concentration at 633 nm.