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A novel technique to measure the sucrose concentration in hydrogel sucrose solution using two dimensional photonic crystal structures

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ABSTRACT

We propose a novel technique to measure the concentration of sucrose in PAm-hydrogel sucrose solution using two dimensional photonic crystal structures consists of air holes. PAm-hydrogel is an organic hydrogels, which is used as biomedical applications. The principle of measurement is based on the linear variation of photonic band gap with the change of dielectric constant of the solution infiltrated in air holes of photonic crystal structure. Plane wave expansion method is used to find the band gap and linear variation ($R^2 = 0.9949$) of photonic band gap with respect to sucrose concentration is observed. Besides this, an excellent linear variation ($R^2 = 0.9949$) of transmitted intensity of light with respect to sucrose concentration is also seen. Since the simulation is based on optical principle, it gives accurate results. This suggests the possible use of 2-D photonic crystal structure as a sucrose sensor. Experimental procedure for measuring the concentration of sucrose is also mentioned.

1. Introduction

Photonic crystals are dielectric structures, where the materials permittivity is described by periodic function [1] that can depend on one, two or three variables and accordingly one obtains a 1-D, 2-D or 3-D photonic crystal structure [2]. Due to the periodicity of permittivity, lattice configuration and index contrast in photonic crystal structure, electromagnetic wave of defined frequency cannot propagate through the crystal structure. This results in a photonic band gap similar to electronic energy gap in semiconductor [3]. Interestingly the photonic band gap can be changed by changing the dimension and dielectric constants of repeating units. For example a 2-D photonic crystal structure realized by drilling a number of air holes on the glass plate. It is found that the photonic band gap can be changed by changing the dimension of air holes, their spacing. Further, if the dielectric constant of air hole regions is changed by introducing some other materials, the photonic band gap also changes. As the intensity of transmitted light from such structure depends on the photonic band gap (wavelength corresponding the photonic band are not transmitted), one can relate the concentration of sucrose with intensity of transmitted light coming from the photonic crystal structure. We use this principle to calculate the sucrose concentration in PAm-hydrogel sucrose concentration.

Polyacrylamide (PAm) is well known organic compound and commonly used hydrogel. PAm hydrogels are clear and homogeneous on a macro level but it is complex and inhomogeneous on molecular level. Through neutron scattering and light scattering measurements it has been found that PAm-hydrogels are not homogeneous and should be regarded as random network [4]. It displays high compatibility with proteins as it is used in numerous biological applications such as gel electrophoresis. It has poor optical properties due to in-homogeneity. Hydrogel have been extensively implanted in various biomedical applications such as soft contact lenses [5] or intraocular lenses, soft tissues replacement and wound managements [6], some forms of prostheses [7,8], artificial organs [9], controlled drugs delivery and other pharmaceutical uses [10,11]. Apart from this, optical applications for hydrogels such as use in laser fabrication [12], as laser surgery aids [13] or as a medium for imagery biological structures via confocal scaling laser microscopy [14] are being realized.

Since the optical clarity of polyacrylamide (PAm) hydrogel matrix could be enhanced through utilization of the additive sucrose, we investigate the effect of sucrose in PAm-hydrogel optical characterization (photonic band gap, intensity of transmitted light) using of photonic crystal structure.

We use plane wave expansion method (PWE) to compute the photonic band gap. The reason for opting PWE is that it provides high accurate results. FDTD though can be used but gives spurious

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results, which appears during the response spectrum analysis, hence is not suitable for our investigation.

In this paper we have discussed methodology of plane wave expansion (PWE) in Section 2. In Section 3, simulation results and discussion are made. Finally, conclusions are drawn in the Section 4.

2. Methodology

The photonic crystal which we have considered for simulations of photonic band gap is a square type 2-D photonic crystal which is shown in Fig. 1.

From Fig. 1, it is seen that 2-D photonic crystal consists of air holes of radius (R) 0.4 μm and lattice constant (a) of 1 μm. The photonic band gap of material changes with the change of dielectric constant of air holes, background or both. Apart from this the same can be changed by changing the radius of air holes, lattice spacing or both. In this case, PAm-hydrogel solutions with different percentage (c) of sucrose are infiltrated in the air holes on silicon substrate having dielectric constant (eb) 11.7.

When one investigates 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

$$-\left\{\frac{\partial}{\partial x}\frac{1}{\in(r_{||})}\frac{\partial}{\partial x}+\frac{\partial}{\partial y}\frac{1}{\in(r_{||})}\frac{\partial}{\partial y}\right\}H_z(r)=\frac{\omega^2}{c^2}H_z(r_{||}) \quad (1)$$

Here $r_{||}$ is 2-D 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 Eq. (1), the eigen value for Fourier expansion coefficient is obtained as

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

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

$$\chi(G_{||})=2f\left(\frac{1}{\in_1}-\frac{1}{\in_2}\right)\frac{J_1(G_{r_{||}})}{G_{r_{||}}} \quad (3)$$

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

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

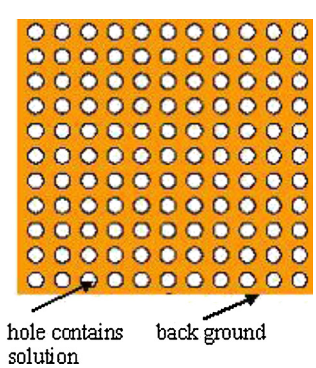

Fig. 1. Square lattice 2-D photonic crystal having holes of radius 0.4 μm and separation between two holes is 1 μm.

Table 1
Dielectric constant of PAm-hydrogel sucrose solution with varying concentration of sucrose.

% (w/v) of sucrose concentration	Dielectric constant (ea) of PAm-hydrogel sucrose solution
0	1.93
10	1.94
20	1.96
30	1.98
40	2.00
50	2.02

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

3. Simulation results and discussion

Table 1 shows the values of dielectric constants (ea) of PAm-hydrogel sucrose solution with respect to sucrose concentration [15].

Simulations are made by using plane wave expansion method for finding the photonic band gap of photonic crystal structure with PAm-hydrogel sucrose solution in the air holes. The simulation results for concentration 0 w/v (%), 10 w/v (%), 20 w/v (%), 30 w/v (%), 40 w/v (%) and 50 w/v (%) are shown in Figs. 2–7, respectively.

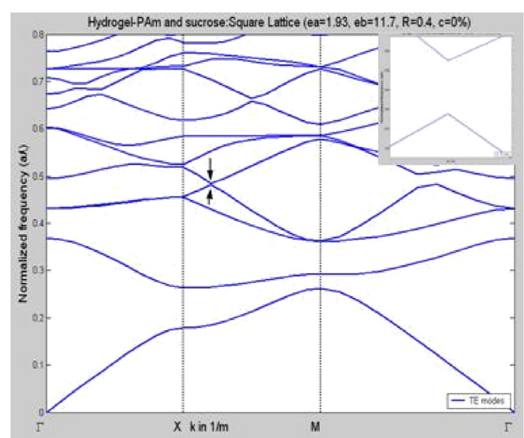

Fig. 2. Simulated dispersion diagram of photonic crystal for 0% of sucrose concentration.

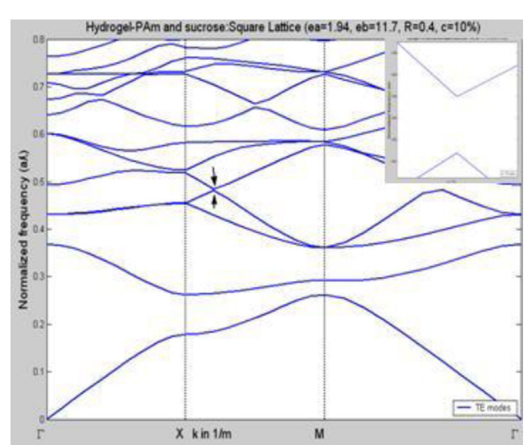

Fig. 3. Simulated dispersion diagram of photonic crystal for 10% of sucrose concentration.