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Design of photonic crystal based ring resonator for detection of different blood constituents

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ABSTRACT

In this paper a photonic crystal based ring resonator structure (PCRR) which can sense different bio-constituents in blood in the wavelength range of 1530–1565 nm for biomedical applications has been successfully demonstrated. Simulation and analysis has been done for Biotin–Streptavidin, Bovine Serum Albumin, Cytop (polymer), Ethanol, Glucose solution (40gm/100 ml), Hemoglobin, Blood Plasma, Polyacrylamide and Sylgard184. Finite Difference Time Domain (FDTD) method has been used for the analysis. MEEP (MIT Electromagnetic Equation Propagation) and MPB (MIT Photonic Bands) simulation tools have been used for modeling and designing of PCRR and IPKISS software framework has been used for generation of mask design which can be used for the fabrication of the PCRR sensor. The optical properties of different bio-constituents are studied and the normalized transmitted output power, transmission wavelength and Q factor have been observed for different blood-constituents which can be used for blood analysis.It has been observed that for little change in dielectric constant (ϵ) according to the blood-constituent taken there will be a moderate shift in the transmitted output power, transmission wavelength and quality factor and hence it acts as a sensor. This indicates that it is highly sensitive even for little change in refractive index. Our designed sensor has achieved sensitivity of 343 nm/RIU.

1. Introduction

Blood analysis plays an important role for detection and prevention of hematological disorders which are responsible for causing many Non-Communicable diseases (NCDs) such as cardiovascular diseases, cancers, diabetes and respiratory diseases which are responsible for 36 million deaths each year worldwide as reported by the World Economic Forum and the Harvard School of Public Health (September-2011) [1]. Human blood is a complex, highly functional body fluid which is composed of more than 4000 bio-constituents. Blood plasma constitutes 55% of human blood fluid and contains proteins such as albumin, glucose, vitamins, minerals, hormones, enzymes, red blood cells (RBCs which contain hemoglobin) and white blood cells (including leukocytes and platelets).The dielectric parameters of blood are of great relevance for various medical applications such as cancer cell detection, dielectric coagulometry and understanding physical, biological and chemical properties of different blood constituents [2–8].

In conventional 'Blood analysis' method, blood sample is needed to be collected, preserved and transported to the laboratories where time taken for analysis can range from 12–72 h [2–8]. There are two important detection methods for optical biosensing: fluorescence based detection method and label-free detection method [9]. The fluorescence-based detection method is highly sensitive where intensity of fluorescence signal detects the presence of target molecules which are labeled with dyes but in this method quantitative analysis is challenging [9,10]. Label-free detection method is suitable for ultra-small detection volumes where the target molecules are detected in their natural form and it can measure refractive index (RI) induced by molecular interactions very easily [9,10]. For sensing RI change various optical biosensors have been designed using Bragg-gratings [11], Mach–Zehnder interferometers [9,12] and Micro-ring resonators [9,13–18]. Among them, conventional micro-ring resonator waveguide can provide very high sensitivity due to high quality factor of resonant peak in output spectra but it has more bending and radiation losses due to reduction in ring-radius [13–18]. Also, Optical waveguides /photonic crystal fibers (PCFs) [9,13], Surface Plasmon Resonance (SPR) [19], Fabry–Perot Interferometer [9,20,21] measures refractive index change and can be used for bio-sensing but the reported sensor is quite large with small Q-factor [9,22]. Photonic crystal ring resonator (PCRR) based sensor provides very high sensitivity

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with ultra low bending loss and excellent light confinement [22,23]. PCRR based sensors are reduced in size and have quite large Q-factor [10]. In the present work, a PCRR based sensor has been designed and simulated for detection of different blood components and the sensing characteristics such as output power, resonant wavelength and Q-factor are investigated. Our modeled and designed sensor is light-weight, miniature in size and very compact and can be fabricated as a lab-on-chip sensor.

2. Theory

In photonic crystal, refractive index (RI) is periodically modulated with the period of the order of a wavelength [24,25]. Photonic crystals exhibit property called as 'photonic band gap (PBG)' and act as 'Optical insulator' [24,25]. These PBGs form frequency bands within which transmission of the electromagnetic wave is forbidden irrespective of the propagation direction [24,25]. By defect engineering the lattice site can be perturbed, the photonic band gap property can be altered and perfect control of light propagation and radiation can be achieved within the photonic crystal [24,25].The propagation of light in photonic crystal is explained by Eq. (1) which is obtained by solving Maxwell's electromagnetic equations [24].

$$\nabla \times \left(\frac{1}{\epsilon} \nabla \times H\right) = \left(\frac{\omega}{C}\right)^2 H \tag{1}$$

In the above Eq. (1), 'ϵ' is permittivity (dielectric function $\epsilon = \eta^2$, where 'η' is the RI), 'ω' is frequency. The above Eq. (1) tells that the frequency 'ω' is inversely proportional to the dielectric function 'ϵ'.

To increase the sensitivity of the photonic crystal structure, the ring resonator waveguide structure has been used [22,23]. The circulating nature of the resonant mode creates an extremely long effective interaction length (L_{eff}),which is determined by the Eq. (2) and hence ring resonator renders better sensing performance [9,23].

$$L_{eff} = Q\lambda/(2\pi\eta) \tag{2}$$

In the above Eq. (2), 'Q' is the resonator quality factor (Q factor) representing the number of round trips that circulating light can make along the ring resonator, 'λ' is the resonant wavelength and 'η' is the refractive index of the ring resonator [9]. In ring resonator, the resonance or output power of the waveguide alters with the change in refractive index of bio-sample taken into consideration. The variations in the resonance resulting from the interaction of biological elements and bio-constituents can be captured and used for sensing applications [9–14].

In this paper, we have used MEEP simulation tool which is a free Finite Difference Time Domain (FDTD) simulation software package developed at MIT to model electromagnetic systems [28–30]. It implements FDTD approach where sampling of continuous electromagnetic field in a finite volume of space takes place for computation of transmission flux at each frequency 'ω' [28–30] and is determined by Eq. (3) given below:

$$P(\omega) = Re\, \hat{n} . \int E_\omega(x)^* \times H_\omega(x)\, d^2x \tag{3}$$

To find the value of $P(\omega)$, MEEP computes the integral $P(t)$ of the Poynting vector at each time, and then Fourier-transform the value obtained. The flux at the specified regions and the frequencies that we want to compute can be computed by MEEP [28].

3. Sensor design

We have proposed a PCRR structure with rods in air configuration for sensing different bio- constituents present in blood such as Biotin–Streptavidin, Bovine Serum Albumin, Cytop (polymer), Ethanol, Glucose solution (40 gm/100 ml), Hemoglobin, Blood Plasma, Polyacrylamide and Sylgard184. When the sensor device will be dipped in the blood sample, the air will be replaced by bio-constituents. When the light will pass through the photonic crystal ring resonator, the interaction of light and bio-constituents will take place. The propagation of light in the photonic crystal will vary with respect to the different dielectric constants of the bio- constituents. Design of the photonic crystal ring resonator device is shown in Fig. 1 given below:

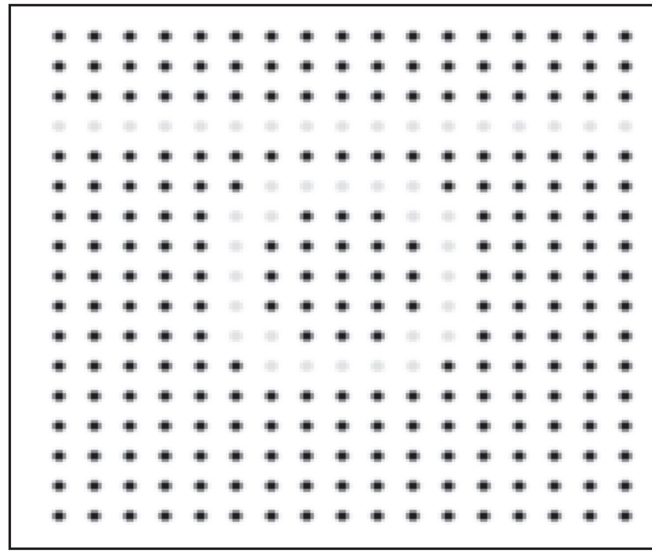

Fig. 1. Design of the photonic crystal ring resonator (PCRR) structure.

Designing and simulation of PCRR is done with the help of MEEP tool. Design specifications are given below:

1. Square lattice structure of matrix 15×20.
2. Rods in air configuration.
3. Thickness of Perfectly matched layer (PML) = 1.0 a.
4. The size of computational cell is 17 x 17.3205 x 0
5. Resolution = 10.
6. Lattice constant 'a' = 1 μm.
7. Radius of rods 'r' = 0.2 μm.
8. Dielectric constant of silicon slab = 12.
9. Dielectric constant of background of the photonic crystal will change with respect to bio-sample taken into consideration.
10. Number of frequencies at which flux is calculated = 260.
11. Polarization = TM.
12. For simulation of individual blood component, approximate Elapsed run time = 6.21193 s.

MEEP uses "dimensionless" units, where the values of ϵ_0, μ_0 and 'c' constants are unity. The transmission spectrum is obtained for different bio-constituents present in blood. The dielectric constant (ϵ) of different bio-constituents has been taken into consideration. The changed dielectric constant (ϵ) can be compared with existing dielectric constant (ϵ) values of each constituent maintained in database for further clinical analysis and detection.

In the present work, we have used MPB (MIT Photonic Bands) tool for computing band structure [31]. MPB solves the Eigen states and Eigen frequencies of the Maxwell's equation which is the output of MPB. Band structure can be obtained by plotting Eigen frequencies versus 'k' points [31,32]. MPB simulation details are given below for the designed PCRR sensor.

1. Computations have been done for 260 bands with $1.000000e^{-07}$ tolerance for TM polarization.