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Photonic Crystal-Based Micro Interferometer Biochip (PC-IMRR) for Early Stage Detection of Melanoma

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ABSTRACT

The paper describes a unique approach for a label-free biosensor designed for early-stage detection of malignant and invasive melanoma. Refractive Index variation analysis plays a vital role in the photonic crystal-based sensor design. The photonic crystal-based micro interferometer biosensor has been designed in rods in air configuration. The design comprises a hexagonal ring structure between two bus waveguides forming sensing and reference arms. The early-stage diagnosis of melanoma is dependent on the comparison of normal cells against affected cells. The diagnosis is conducted using the arms of the interferometer. The sensitivity of the biosensor is determined by the phase shift/wavelength difference between the arms of the interferometer sensor. The sensitivity of the designed sensor is 4000nm/RIU. The simulations are done using the FDTD technique. The relative shifts in frequency and wavelength are due to the refractive index deviation in the sensing arm. Quality factor is obtained at 10654.3 for the wavelength 1550 nm.

Keywords: Bus waveguides, early stage diagnosis, FDTD, interferometer, melanoma, photonic crystal, quality factor, refractive index deviation

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INTRODUCTION

Cancer is caused by uncontrolled cell division in the body and comprises about more than 200 different forms, depending on the origin of the uncontrolled growth in the body. Cancer is diagnosed in terms of stages depending on the rate at which cancer cells spread in the

body. The stages of cancer are suspected from the occurrence of tumours and their impact on nearby lymph nodes. Skin cancer is the most commonly occurring cancer in Western countries like the USA, Canada etc. Squamous and basal cancers are the most commonly occurring skin cancers. Melanoma is the most dangerous skin cancer, with an occurrence of 1% among the population. The stages of melanoma depend on variations in skin texture.

Photonic crystal- (PC) based optical sensors have emerged as a unique solution in early detection of cancer. Although sensors based on conventional techniques are well established, photonic crystal-based sensors have gained the attention of researchers across the world (Girijamba, Srikanth, & Sharan, 2016). PC is characterised by periodic arrangement of rods (for rods in air) or holes (for holes in slab) (Pierre, Villeneuve, & Joannopoulos, 1996). The benefit of using PC is that it modifies the size and location of the holes/rods in the lattice structure, allowing the output spectrum to be modulated to sense even minute values; this cannot be achieved using traditional optical sensor-based devices (Joannopoulos, Johnson, Winn, & Meade, 2008). PC provides a unique solution for practical applications, where the monitoring of refractive index (RI) variations are important, such as monitoring of changes in complex structures bio analytes.

Sharan and Sharma (2015a) presented that for a small RI change, a moderate shift in the frequency is observed and hence, concluded that PC can be used as a sensor. Sharan and Sharma (2015b) proposed an optical-sensor design for urine analysis for diabetic applications. The sensor design consisted of a two-dimensional PC ring resonator structure (Mallika, Bahaddur, Srikanth, & Sharan, 2015) to achieve a Q factor of 210. Mondal, Sharan and Hussain (2017) presented the modelling of the Fiber Bragg Grating (FBG) for structural health monitoring application; it was geometrically designed in the wavelength window of 1.568-1.580 μm.

Despite the vast research conducted by Sharan and Sharma (2015c) in the field of PC-based sensors, commercialisation of such sensors is not yet achieved. So, new techniques must be developed to make PC-based sensing more cost effective. Also, sensitivity needs to be increased to measure comparatively lower magnitudes of RI variations. This can be done by manipulating the lattice parameters and structure of the PC, for example, by varying the rod diameter or by changing the structure of PCRR.

In this paper, we present a PC-based Interferometric Micro Ring Resonator (PC-IMRR) structure. The simulation of the operation of the sensor was carried out using the Finite Difference Time Domain (FDTD) method (Taflove, Oskooi, & Steven, 2013). A comparison of the results of the sensitivity tests was also done.

MATERIALS AND METHOD

A unique hexagonal-shaped resonant cavity was modelled using bus. The proposed model of the resonant structure reduced the scattering losses and increased light confinement. Therefore, the model was proposed to improve various features such as sensitivity and Q factor, among others. The Plane Wave Expansion (PWE) and FDTD methods were employed for obtaining the required PBG and normalised transmission spectra for the proposed structure. This paper

covers the modelling of the designed structure and also presents a simulation of the device's use. The results were later analysed and discussed. The theoretical analysis of 2D PC was carried out using the PWE method by Pendary (1996) and the FDTD method. The PBG of periodic and non-periodic structures and propagation modes were calculated using the PWE method primarily.

$$\nabla \times \left(\frac{1}{\varepsilon(r)} \nabla \times E(\mathrm{r}) \right) = \frac{\omega^2}{c^2} E(\mathrm{r}) \tag{1}$$

The PWE method was realised using Maxwell's equations where, Ɛ(r) is the dielectric function and ω is the angular frequency, E(r) is the electric field of the periodic structure, and 'c' is the speed of light in free space.

The solution of Equation (1) was represented in the form of a band structure. The spatial detention of the photon in the PC was achieved through the introduction of defects. The propagation of electromagnetic modes inside the PC structures was studied using the FDTD method that was introduced by Yee (1966). The FDTD was considered the most significant solution to Maxwell's equation, given its simplicity. In this simulation, the FDTD mesh size and time step were $\Delta x = a/20$ and $\Delta t = \Delta x/16$, respectively. The 2D FDTD method was used to obtain the transmission spectrum of the proposed sensor. The performance measurement parameter for the proposed sensor was the Q factor. The Q factor measured the losses in the cavity.

$$U(\mathrm{t}) = U(O) \exp\left[\frac{-(\omega_o t)}{Q} \right] \tag{2}$$

The Q-factor was calculated using [11], where λ_r is the central wavelength and $\Delta\lambda$ is the channel bandwidth.

$$\mathrm{Q} = \frac{\lambda_r}{\Delta\lambda} \tag{3}$$

PROPOSED DESIGN

The proposed design is a PC-based Interferometric Micro Ring Resonator (PCIMRR) consisting of two bus waveguides and a hexagonal bent waveguide using the rods in air configuration. The design parameters used were: lattice size, 21x21nm; lattice constant, 200 nm; rod diameter, 900 nm; the lattice constant a, 520 nm; radius of non-defected rod, 115 nm. The proposed sensor is the design using the square lattice PC. The total amount of rods in 'X' and 'Z' directions is 22 and 19, respectively, as shown in Figure 1.

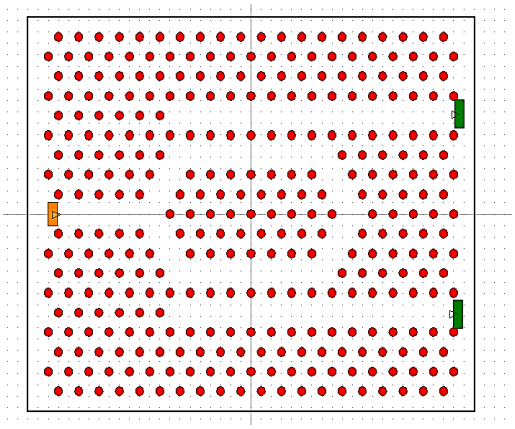

Figure 1. PC-based micro interferometer biosensor

The hexagonal lattice structures designed with silica as the base material comprised circular rods based on slab. As can be seen in Figure 1, two bus structures were created to observe the shift in resonance wavelength. The operating wavelength was chosen as 1550 nm in order to achieve higher sensitivity. Different levels of bio samples were placed in the air and the corresponding shift in resonance wavelength was observed. The effect of changes in RI on the sensor was also analysed.

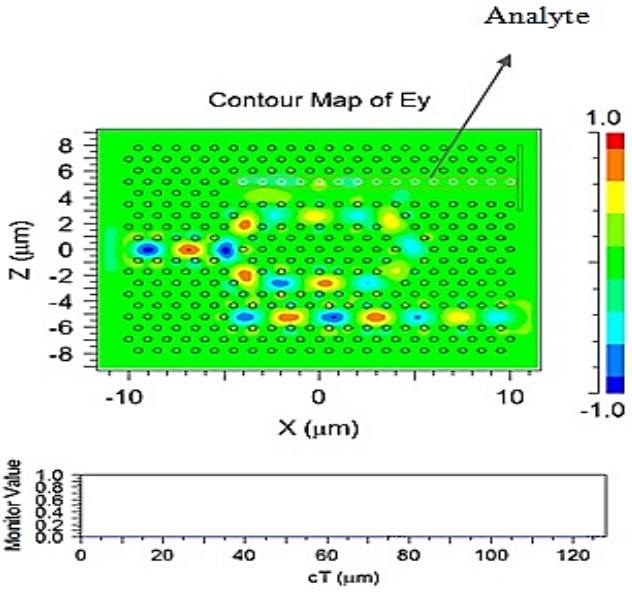

Figure 2. Excitation inside the interferometric cavity

The above contour depicts the excitation inside the interferometer. The light travelling from the micro hexagonal ring is guided to one of the two independent bus waveguides. Two excitation monitors were kept at the ends of the bus waveguides. Of the waveguides was considered the sensing waveguide, while the other was considered the reference waveguide. The sample was placed on the sensing arm so as to compare the phase variation of the sensing arm and reference arm.

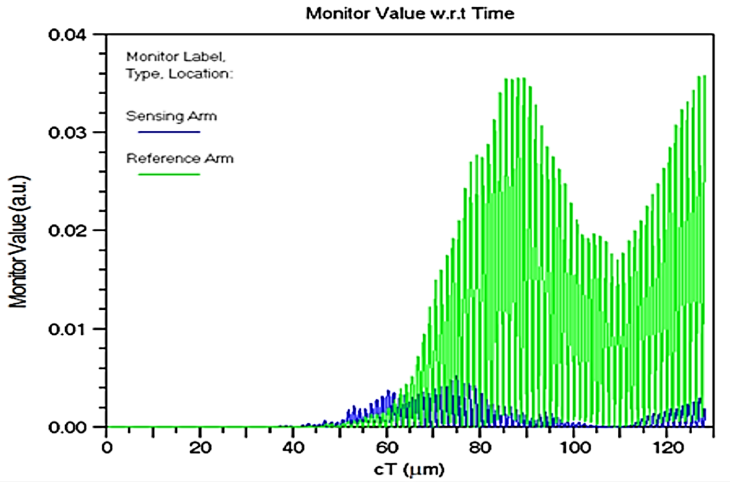

Figure 3. Light intensity comparison of the two bus waveguides

Figure 3 depicts the intensity comparison for the two bus waveguides, one with the normal melanin sample in the sensing arm. The intensity value of the reference arm was 0.037 a.u. and 0.005 a.u. Intensity variation and deviation by wavelength can be easily compared; hence, sensitivity can be calculated.

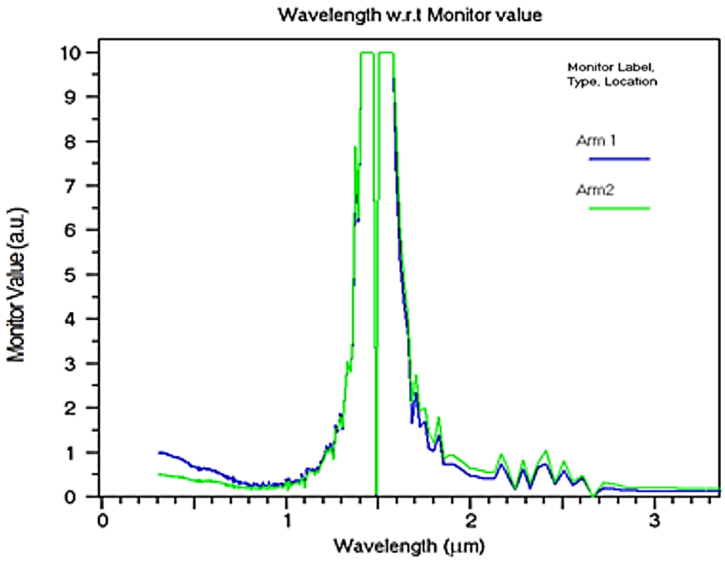

Figure 4. Light intensity (monitor value) w.r.t. wavelength for the comparison of bus waveguides

Figure 4 illustrates the typical behaviour of wavelength with respect to monitor power, where the responses from the reference and sensing arms were recorded and compared. They were found to be identical, with a negligible variation of a peak intensity value of 9.87 a.u. at wavelength 1.405 µm, where the source was 1.55 µm.

RESULTS AND DISCUSSION

Figure 5 demonstrates the light intensity with respect to the wavelength variation of the two arms, with each holding different samples. The intensity monitor placed at one arm depicted the wavelength response of the epidermis and the intensity monitor located at the other arm showed the response of the normal melanocyte. Due to high absorption of light, the melanin response lagged by 0.02 µm.

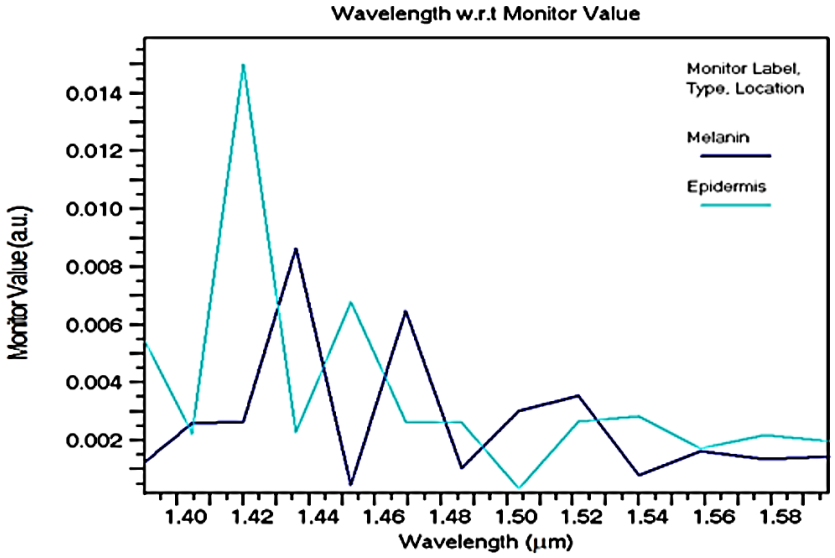

Figure 5. Light intensity (monitor value) w.r.t. wavelength for the comparison of bus

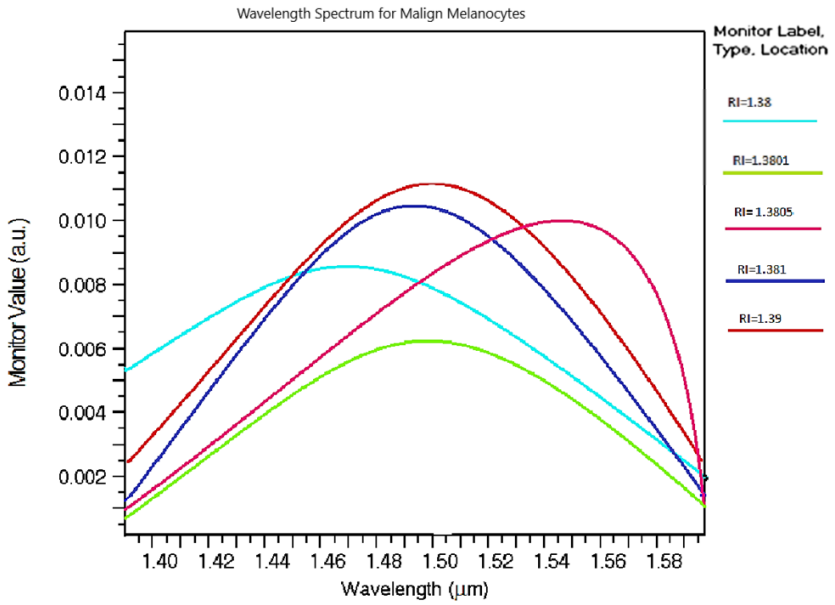

Figure 6. Wavelength response for malign melanocyte values ranging from 1.38+0.01

The figure shows the wavelength spectrum for malign melanocytes, where the peak values of malign cells occurred at the wavelength range of 1.45 to 1.55 µm.

CONCLUSION

Our work was aimed at minimising the size of devices at nano-scale for integration with integrated optical chips. The designed device can be used extensively by the layman with minimum training and if produced in bulk, will be a low-cost device. We designed and developed the sensor for skin cancer detection using bio analytes. Each element of the sample has a unique RI and our design approach involved the use of a unique RI for each element as the signature of the element. The presence of the disease can be established by matching the signature of a cancer-infected cell in the sample. The accuracy and reliability of the results were demonstrated using state-of-the-art simulation tools. The result obtained shows sensitivity of 4000 nm/RIU and a Q factor of 10654.3. The figures were much higher than the previously published results of 250 nm/RIU for Mach-Zehnder-type optical sensor implementation.

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