Photonic Crystal Based Sensor for DNA Analysis of Cancer Detection

Sandip Kumar Roy and Preeta Sharan

Abstract This paper reports a novel method for detecting cancer with a small integrated lab-on-a-chip. The existing biosensors measure the interactions between the biomolecules that are absorbed on the surfaces of biochips. In this paper, a two-dimensional Photonic Crystal (PhC) ring resonator is proposed for DNA analysis of normal and cancerous blood cells. For modeling and simulation of the sensor, Finite-Domain and Time Domain (FDTD) method is used as the backend algorithm using MEEP (MIT Electromagnetic Equation Propagation) tool. Simulation shows that, for a small change in refractive index (RI) of DNA of blood, there is a change in the spectrum. Thus, the sensor can be used as a highly sensitive sensing device for the change in DNA properties because of cancer.

Keywords Cancer · Photonic crystal · Refractive index · MEEP

1 Introduction

Among the most fatal diseases, cancer is in the third position in India. By next quarter of a century, globally reported cancer cases may get doubled. Half of the reported cases will be from developing countries. Cancer is a generic term used to classify cause of a huge set of diseases. These diseases primarily have a common symptom of uncontrolled cell proliferation which cannot be controlled by the normal cell kinetics regulation mechanism. In case of cancer, a normal cell multiplies continuously without control, leading to the development of tumors or an

S. K. Roy (✉)
AMET University, Chennai, India
e-mail: sandipr@hotmail.com

P. Sharan
The Oxford College of Engineering, VTU, Bengaluru, India
e-mail: sharanpreeta@gmail.com

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abnormal rise in the number of dispersed cells like the blood corpuscles. Occurrence of cancer may happen in any organ or tissue of the body. Research has not established relation of cancer with age; however, mostly it is found to occur with old age. Cancer risks increase with lifestyle and exposure to cancer-causing environment like tobacco. Infections can act as a cause to cancer but as such this is not an infectious disease. Exposure to pollutants like industrial effluents, chemical waste, therapeutic drugs, and ionizing radiation can increase the cancer risk. Lifestyle habits like junk diet, cigarette, alcohol, and exposure to industrial waste attributed to 50% cancer risks [1].

Damage to DNA is the root cause of cancer. In case of a normal cell, a damaged DNA gets either repaired or the cell ceases to exist. In case of cancer, the damaged DNA continues to make new cells even though the body may not require them. This results in unwanted tissues and manifests as either tumors or cancer [2].

When altered DNA starts evolving a different set of tissues until the cells do not become invasive, the condition is said to be a tumor. If the cells start propagating to different unaffected parts of the body thus forming a different set of tissues, the condition is said to be malignant or cancer.

According to the American Cancer Society, cancer report for the year 2013–2014, globally there are around 10 million people affected by cancer out of which 6.5 lakhs are in India. About 39,620 deaths of all age group women in US are due to breast cancer [3].

In the current work, we have presented a sensor for the DNA analysis and detection of cancer. The 2D PhC ring resonator structure is designed and simulated. The ring resonator structure is used because it provides higher accuracy results. For small changes in the optical parameters of the analyte, the design provides a significant shift in output transmitted power.

2 Theory

PhC is composed of periodic dielectric nanostructures with sandwich of materials with low and high dielectric constant in 1D, 2D, and 3D. PhC affects propagation of light inside the structure. Because of the periodicity of structure, PhC causes Photonic Band Gap (PBG) where the propagation of light is completely prohibited for certain frequency ranges (band). By means of defect engineering, the band gaps become porous for certain frequencies and light can pass through the PBG [4].

PhC possesses two types of polarization by symmetry: the transverse magnetic (TM) in which the electric and magnetic fields are orthogonal to one another, and the transverse electric field (TE) in which the electric and magnetic fields are in same phase [5].

Light propagation in PhC is governed by the master Eq. (1). This is arrived at by solving Maxwell's electromagnetic equations:

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

H Photon's magnetic field
ε Permittivity
ω Angular frequency of resonance.

As per Eq. (1), the angular frequency of propagating light (ω) is dependent on the permittivity (ε) of medium. As dielectric function ε changes, the ω changes. This is the principle behind the use of PhC structures as sensor. Methods like effective refractive index, spectroscopy, and optical imaging are there but because of small input change, output sensitivity is significantly low.

Ring resonator waveguide structures are used to increase sensitivity of the sensor. In resonator structures, output power of the waveguide alters as the refractive index of the sample is changed. The variation in resonance can be captured and thus the structure can be used for sensing applications [6].

The focus of the work is to design a 2D PhC ring resonator-based lab-on-a-chip which can be used for the DNA analysis of cancer detection. The ring resonator structure is used to increase the sensitivity and quality factor of the design. The RI of normal and cancerous DNA is considered for the change in behavior of the medium of each case. Distinct displacement in output transmitted power and frequency is obtained for normal and cancerous DNA cells [7].

3 Sensor Design

The design structure of PhC sensor is a 2D square lattice ring resonator structure. The square lattice with rods in air configuration is used. This sensor is implemented using a ring resonator defect engineering. Resonators are waveguides shaped in a ring structure. We place the analyte in the structure and a spectrum, which is unique for different cells in the sample and is obtained at the end of the waveguide. For analysis of time domain and frequency domain, we used the data of dielectric constants of DNA cell (normal and cancerous) from published data [8, 9] (Fig. 1).

MEEP/MATLAB software used to develop source code for modeling and designing of PhC waveguide. The MEEP tool uses scripting language where a code is written and simulation is carried out for band gap structures (frequency domain) and transmission spectrum with varying time period (time domain). Results obtained are represented in graph and analyzed.

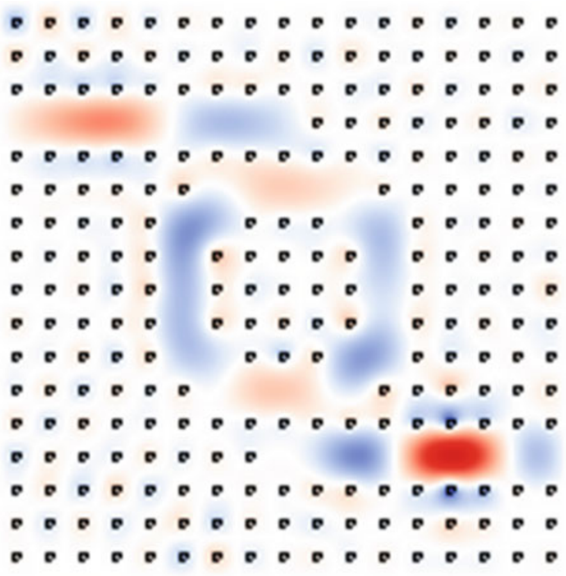

Fig. 1 2D PhC-based biosensor design using ring resonator and rods in air configuration

The design parameters considered are

1. Lattice constant (a) = 1
2. Rods in air with radius (r) = 0.2 μm
3. Silicon rods with dielectric constant = 12
4. Rods height = Infinity
5. Light's wavelength = 1555 nm
6. Dielectric constant of air is replaced with that of sample.
7. Gaussian pulsed light source used.

Detailed study has been done on variation in medium properties of DNA for normal and cancerous cells. The refractive index of each case is taken as input for MEEP.

4 Design and Modeling

Software package MEEP from MIT used for design is a free software for FDTD simulation to model electromagnetic systems, along with MPB. In this technique, discrete grid is drawn in the available space. Using discrete time steps, with time the fields are evolved. As the grids and the time steps are made further refined, a closer approximation for the continuous equations is obtained.

In MEEP, FDTD is implemented to solve time-varying Maxwell's equation. In FDTD method, a variable or constant spacing of rectangular grid points is discretised. FDTD method helps in solving Maxwell's equations directly. MPB is a frequency-domain analysis tool and implements the electromagnetic modes of periodic dielectric structures. MPB does a direct computation of the eigenstates values of Maxwell's equations. Each field computed has a definite frequency. MATLAB is used to plot graphs. In RSOFT photonic suite software, RSoft CAD is a program for passive device simulation. Band Solve module is used in our work.

5 Experiment and Results

In this paper, variation of output amplitude is compared with the introduction of normal cell and infected cell. The spectral results are simulated and tabulated for normal and cancerous DNA cells [10]. Figures 2, 3, 4, and 5 show the transmitted and reflected spectrum of normal and cancerous DNA. The result of simulation shows shift in wavelength for both normal and cancerous DNA. The peak frequency obtained for normal DNA is 275 and for cancerous DNA is 259 MEEP unit. Thus, the PhC sensor has a high-quality factor.

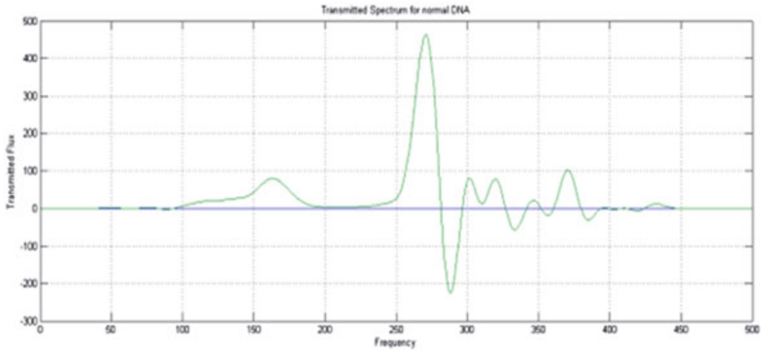

Fig. 2 Normal DNA—transmitted spectrum

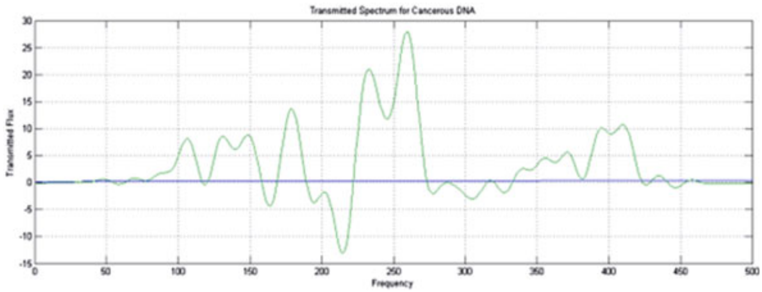

Fig. 3 Cancerous DNA—transmitted spectrum

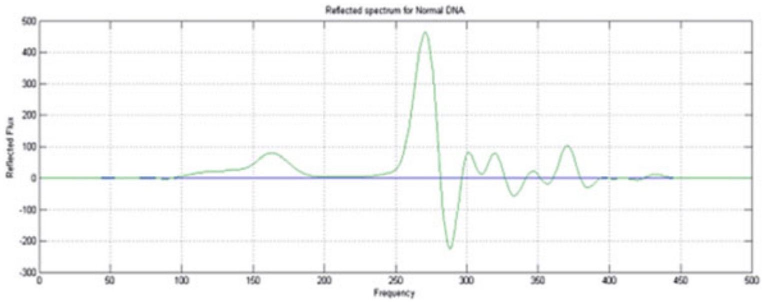

Fig. 4 Normal DNA—reflected spectrum

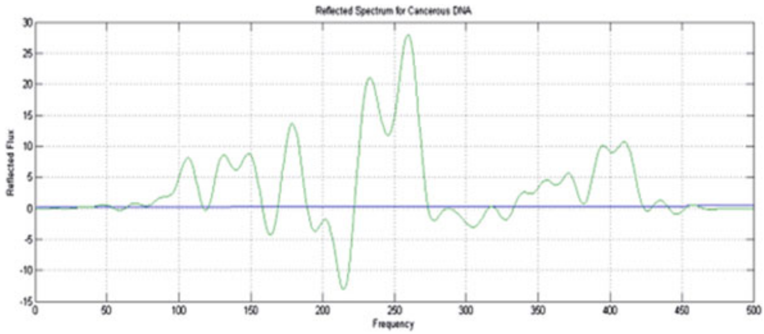

Fig. 5 Cancerous DNA—reflected spectrum

Fig. 6 Cancerous versus normal DNA—overlapping transmitted spectrum

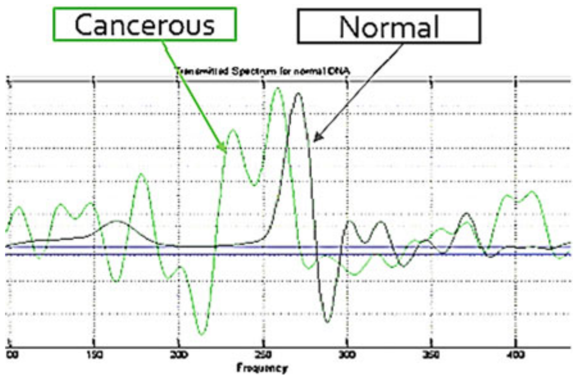

Figure 6 shows overlapping transmitted spectrum of DNA for normal versus cancerous cells. It has been shown that there was a shift in wavelength between normal and cancerous DNA. The graph in green indicates the transmitted flux value for the optical properties of the cancer-affected DNA [11, 12].

6 Conclusion

The work presented in this paper involves design of a PhC-based sensor to detect cancerous DNA. A 2D PhC ring resonator structure designed with rods in air configuration. For normal and cancerous DNA, transmission spectrum is taken using MEEP. Result shows distinct output spectrum for normal and cancerous DNA with a frequency shift of 16 MEEP unit. Thus, the work established that the distinct spectrum can be used as a signature for detection of cancerous DNA.

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