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Design of 1D Photonic Crystal Based Sensor for Detection of Cancer Cells

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Abstract

A one-dimensional (1D) photonic crystal composed of alternating layers of silicon and silicon dioxide (SiO_2) with a defective layer is theoretically designed for the detection of cancer cells. The transfer matrix method is used for the theoretical formulation, and the computational analysis is done using MATLAB software. The transmission spectra of the proposed structure $(AB)^N D(AB)^N$ has been analyzed by using various cell samples as the defect layer, including normal and cancer cells. Different cell samples, such as HeLa, Basal and Jurkat are used as analytes in the defect layer. Several parameters, including sensitivity (S), figure of merit (FOM), and quality factor (Q), have been theoretically estimated to assess the effectiveness of our design. A high sensitivity of 272.8 nm/RIU, high quality factor of 1.3×10^4, high FOM of 5.4×10^3 RIU are observed for our proposed design, which implies that our designed photonic crystal structure may be suitable for cancer detection and other biosensing applications.

Keywords

Photonic crystals, Biosensor, Transfer matrix method, Cancer cells

Introduction

The research field of nanotechnology encompasses several fields of biology, chemistry, physics, engineering, and medicine [1]. Nano compounds play a significant role in biomedical applications due to their unique properties at the nanoscale, which enable highly sensitive and specific detection of biological molecules and processes [2, 3]. In clinical settings all over the world, biosensors are widely used to diagnose a wide range of illnesses and disorders. The use of biosensors at the point-of-care, such as at primary clinics or the bedside, is hampered by the fact that they may call for highly skilled personnel, take a long time to perform assays, are large in size, and are expensive to implement. As a result, point-of-care requires the development of cost effective, trustworthy, user-friendly, and compact biosensing systems.

Nanotechnology may be used in the field of biosensors to treat cancer by multifunctional nanoparticles that can target cancer cells, carry, and release medications in a controlled manner, and detect cancer cells with remarkable accuracy. Nanoparticles, such as gold nanoparticles, quantum dots, and magnetic nanoparticles, are commonly used in biosensing. They can be functionalized with specific biomolecules (e.g., antibodies, DNA probes) to recognize and bind to target biomarkers. The interaction between these nanoparticles and the target molecules can be detected and quantified. Many of the problems preventing the detection and treatment of cancer cells can be solved by using biosensors built with photonic crystal (PC) structures.

PCs are a newly developed kind of nanostructured optical media made of

natural or artificial structures, in which their refractive indices are varied periodically. One of its most important properties is to control the flow of photons [4], which gives an opportunity for several applications to be implemented on their basis. PCs are divided into three categories, namely 1D, two-dimensional, and 3-D structures, depending on their geometry. Some photonic crystals exhibit wavelength ranges for which propagation of photons is forbidden. This region of zero transmission of photons is called the photonic band gap [5], and it arises due to scattering of light in the lattice. The break in the periodicity of PC is known as a defect, which leads to a confined state inside the photonic band gap, called resonant modes. Many researchers have worked on defects in 1D PCs with materials such as GaAs, polymers, etc. [6, 7]. This resonant mode acts as a window inside the PBG, allowing incident light or radiation with resonant wavelengths to pass through the structure. This is due to the strong electric field confinement inside the defect layer region resulting in small changes in the refractive index of the material in defect layer. This corresponds to a change in the position of the resonant mode inside the PBG [8]. This concept is the basis for PC-based biosensors.

In this work, we have proposed a 1D defective PC design for possible cancer cell detection. The proposed design is shown in figure 1. The structural configuration used in this work may be expressed as $(AB)^N D(AB)^N$, where A and B are the different material layers with A being silicon (Si) and B being SiO_2. The transmission spectra of the suggested structure $(AB)^N D(AB)^N$ can be theoretically analyzed using various cell samples as a defect layer, is intriguing, as it suggests that the PC based sensor could potentially distinguish between normal and cancer cells based on differences in their optical properties.

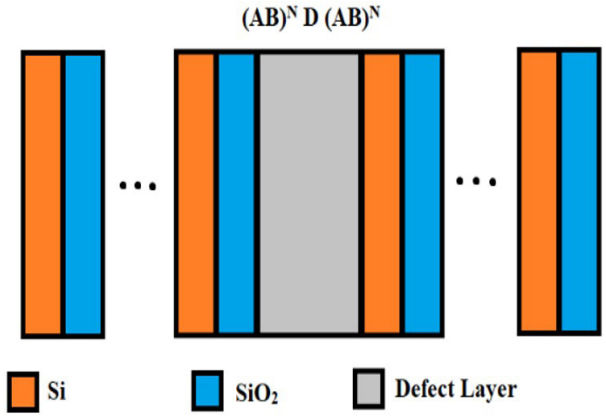


Figure 1: Schematic diagram of the proposed 1D defective PC.

Methodology

Transfer matrix method [9] is used in the theoretical formulation and it analyzes the interaction between plane electromagnetic wave and our designed structure. The proposed design can be explained in terms of a single matrix form, given as:

$$M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \left(m_A m_B\right)^N m_D \left(m_A m_B\right)^N \quad (1)$$

Here, m_{11}, m_{12}, m_{21}, m_{22} are the transfer matrix elements, N is the number periods in the PC stack. m_a, m_b, m_d are the matrix elements of the layers A, B and D, respectively. They are defined as:

$$m_x = \begin{pmatrix} \cos\delta_x & \left(-i/n_x\right)\sin\delta_x \\ -in_x \sin\delta_x & \cos\delta_x \end{pmatrix} \quad (2)$$

δ_x (x = A, B, D) is the phase difference at each layer, which is given by,

$$\delta_x = \frac{2\pi}{\lambda} n_x d_x \cos\theta_x \quad (3)$$

Here, n_x, d_x, θ_x are the refractive index, thickness, incident angle at each layer, respectively. 't' is the transmission coefficient for the designed structure and is given by,

$$t = \frac{4}{abs\left(m_{11} + m_{12} + m_{21} + m_{22}\right)^2} \quad (4)$$

For evaluating the performance and efficiency of the proposed design, the most common parameters, such as sensitivity (S), quality factor (Q), and FOM are taken into consideration [10]. Sensitivity (S) of a biosensor is defined by,

$$S = \frac{\Delta\lambda_R}{\Delta n_D} \quad (5)$$

Where, $\Delta\lambda_R$ is the change in resonant wavelengths in the defect and Δn_D is the change in the refractive index of the cell sample in the defect. Quality factor (Q) is given by,

$$Q = \frac{\lambda_R}{FWHM} \quad (6)$$

Where, λ_R is the resonant wavelength of the defect mode and FWHM represents the full width half maximum of the resonant wavelength. FOM is given by,

$$FOM = \frac{S}{FWHM} \quad (7)$$

Results and Discussion

The proposed biosensor has a structural design of $(AB)^N D(AB)^N$, where the defect layer is placed between the 1D PCs. The 1D PCs are comprised of two layers namely, A and B. In this work, Silicon is taken as 'A' layer, and SiO_2 is taken to be 'B' layer. The refractive index (n) of both the layers is as follows: n_A = 3.3; n_B = 1.45. The thickness (d) of both the layers is fixed at d_A = 50 nm and d_B = 100 nm, respectively. The thickness of the defect layer (d_D) is fixed at d_D = 500 nm. 'N' represents the number of periods of PC in a stack, and it is fixed at N = 5. Figure 2 shows the presence of defect mode in the transmission spectra of PC with a defect.

The defect layer is now loaded with different cell samples,

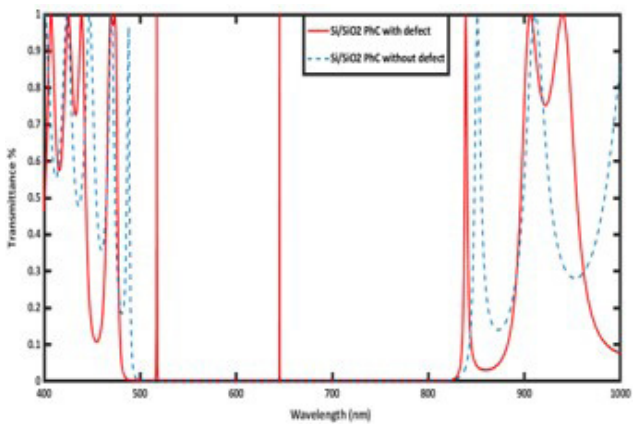


Figure 2: Transmission spectra of the proposed design with and without defect.

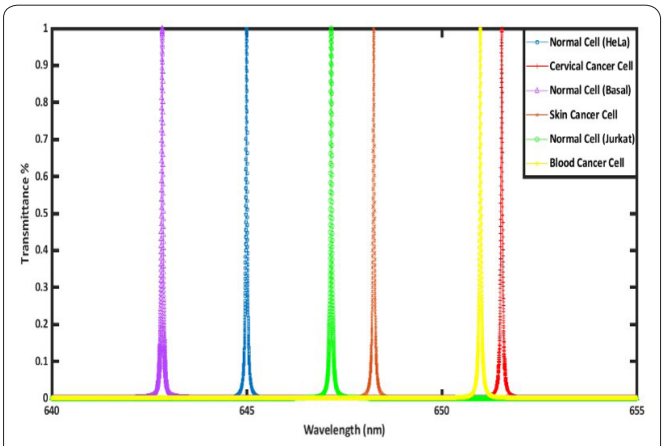


Figure 3: Transmission spectra of our proposed design when the defect layer of thickness 500 nm is loaded with the normal cell and the cancer affected cell of HeLa, Basal, and Jurkat type cells.

and for this study, various cells in normal stage and cancer stage are considered [11]. The different cell samples used in this study are HeLa type cells from the cervical tissue region of our body, Basal type cells from the outer layer of the skin, and Jurkat type cells from the T lymphocyte cell line. Figure 3 shows the comparison of transmission spectra of our proposed design when the defect layer is loaded with the normal cell and the cancer affected cell of HeLa, Basal, and Jurkat type cells, respectively. From the defect modes of each cell sample, their respective resonant wavelengths are identified, which is essential in determining the sensing parameters for our proposed design. Sensitivity (S), quality factor (Q) and FOM are derived from equation 5, equation 6, and equation 7, respectively. Table 1 shows the calculated values of the above-mentioned parameters, and it is evident from table 1 that maximum values of sensitivity (S), quality factor (Q) and FOM are observed. The high sensitivity of 272.8 nm/RIU means that the sensor can sense small changes in refractive index with high accuracy, which is important for detecting small biomolecules or cells. The high-quality factor of 1.3 x 10^4 indicates that the sensor has a narrow resonance linewidth, which leads to higher sensitivity and better selectivity. The FOM of 5.4 x 10^3 RIU is also quite high, which is a measure of the sensor's overall performance. A higher FOM indicates that the sensor is more sensitive and selective, making it better suited for practical applications such as disease diagnosis or drug discovery.

Conclusion

In conclusion, we have theoretically designed a 1D PC-based biosensor with $(AB)^N D(AB)^N$ structure with silicon and SiO_2 as alternate layers. The transfer matrix method is implemented in theoretical analyzation of transmission for our proposed design, and MATLAB is used as a computational tool. The defect layer of 500 nm thickness is loaded with different cell samples, namely HeLa, Basal, and Jurkat cells. The normal and cancer affected cells are considered for this study and from results, maximum values of biosensing parameters such as sensitivity, quality factor and FOM are obtained. These are impressive results for the proposed PC-based biosensor design. Overall, these results suggest that the proposed design has promising potential for biosensing applications and could potentially lead to the development of more accurate and efficient diagnostic tools for detecting cancer or other diseases.

Acknowledgments

None.

Conflict of Interest

None.

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Table 1: Theoretical calculations of biosensing parameters for the proposed design using different cell samples.

Cell name	Cell type	Refractive index	λ_R (nm)	FWHM (nm)	S (nm/RIU)	Q	FOM (RIU)
HeLa	Normal	1.368	644.99	0.05	-	12899.8	-
	Cervical cancer	1.392	651.53	0.05	272.5	13030.6	5450
Basal	Normal	1.360	642.83	0.05	-	12856.6	-
	Skin cancer	1.380	648.25	0.05	271	12965	5420
Jurkat	Normal	1.376	647.16	0.05	-	12943.2	-
	Blood cancer	1.390	650.98	0.05	272.8	13019.6	5456

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