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Analysis and design of optical biosensors using one-dimensional photonic crystals

Ankit Singh [a], Khem B. Thapa [a,*], Narendra Kumar [b]

[a] Department of Physics, University Institute of Engineering & Technology, Chhatrapati Shahu Ji Maharaj University, Kanpur 208024, India
[b] FASC, Mody University of Science and Technology, Lakshmangarh 332311, Sikar, Rajasthan, India

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ABSTRACT

An analysis and design of an optical biosensor is presented considering a one-dimensional photonic crystal, which is in form of periodic dielectric media. In order to study the properties of 1D PC in terms of reflectance (R), transmittance (T), field intensity and sensitivity; we have employed the transfer matrix method (TMM). A design of the optical biosensors is thus proposed by considering the 1D PC structure like $S/(HL)^N/S$ having two different materials of high H and low L refractive indices, respectively, and S represents the substrate. In 1D PC, there exists a defect layer X, breaking the periodic structure as $S/H(LH)^{N/2}/X/(HL)^{N/2}H/S$, and a defect state (resonance mode) will appear at a certain position in the band gap. In our work, we have made theoretical analysis of a perfect optical biosensor using the 1D PC based on label-free optical sensing, which does not use fluorescence based-detection, where porous silicon interacts with biomolecule and reduces its refractive index by biomolecular reaction. The designed sensor identifies the molecule on the basis of two parameters with the change in the characteristic peaks in the obtained curves, that are, the electric field intensity and sensitivity with varying the total thickness of the material. This analysis can be useful to design an optical sensor with 1D PC and to evaluate the performance of biosensors in terms of high sensitivity, resolution or detection limit.

1. Introduction

Science has enabled us numerous devices with easy performance, low cost and high efficiency. In the same way, sensor is also a device, which can sense the physical parameters like temperature, pressure, change in intensity, biomolecules, etc. Today the field of research in sensor development is rapidly increasing because the researchers want to develop the sensor on latest best technology [1]. In 1962, two persons L.C. Clark and C. Lyons originated the first biosensor on which the term enzyme-electrode was adopted [2]. Today different types of biosensors are available such as potentiometric biosensors [3], piezo-electric biosensors [4], immunosensors [5], optical biosensors [6–13], etc. Our interest toward the optical biosensor is more because the optical biosensor is a well-established analytical tool for biomolecular interaction analysis and it has also robustness, simplicity and high sensitivity. Actually, the biosensor typically consists of a biological component, a detector element and a transducer associated with both components [14,15]. Optical biosensor generally based upon two detection protocols, i.e., fluorescence-based detection [16] and label-free detection [17–19], however due to some disadvantages of fluorescence-based detection, people generally use the label-free detection for biomolecular sensing [20]. Biosensors provide some applications in the fields of drug discovery [21,22], environmental monitoring [23,24], food/water [25,26], etc.

2. Theory and methodology

Today people want to fabricate the optical biosensors by using the photonic crystal [27–29] having such different types of properties of materials, which can do complete control over the light propagation [30]. Here, we use the photonic band gap (PBG) [31,32] materials for our calculations of field intensity and sensitivity of optical biosensor by using the laws of optical physics.

2.1. Transfer matrix method

In order to calculate the transmission, reflection, field intensity and sensitivity of 1D multilayered structure, the TMM method [33–37] is the best method. Here, we use the TMM method to

* Corresponding author.
E-mail addresses: ankitkanphysics@gmail.com (A. Singh), khem.phy@gmail.com (K.B. Thapa).

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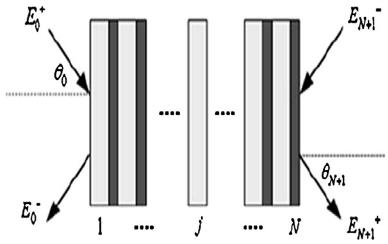

Fig. 1. Schematic diagram for multilayer structure.

calculate each components of the e.m. field within the multilayer structure and transmittance of the considered periodic structure.

Let us assume a multilayer structure, which has the output electric field components $[E_{N+1}^+, E_{N+1}^-]$ with the input electric field components $[E_0^+, E_0^-]$ in which a series of matrices must be obtained, having each interface matrix $M_{i,j}$ between two layers (i and j), and each propagation matrix M_j connecting the beginning and the end within the j as shown in Fig. 1. The total transfer matrix can be achieved by simply multiplying all the interface and propagation transfer matrices as follows:

$$\begin{bmatrix} E_{N+1}^+ \\ E_{N+1}^- \end{bmatrix} = M_{N,N+1} M_N M_{N-1,N} \quad \ldots M_{j,j+1} M_j M_{j-1,j} \ldots M_{1,2} M_1 M_{0,1} \begin{bmatrix} E_0^+ \\ E_0^- \end{bmatrix} \tag{1}$$

This equation can be used to calculate the electric field and transmittance by considering the boundary condition in terms of material parameters and r, t coefficients.

2.1.1. *Interface matrix*

The interface matrices of two different media can be derived from the boundary conditions of Maxwell's equations as

$$\vec{E}_i^{\shortparallel} = \vec{E}_j^{\shortparallel} \tag{2}$$

$$\vec{H}_i^{\shortparallel} - \vec{H}_j^{\shortparallel} = \vec{J} \tag{3}$$

$$\vec{D}_i^{\perp} - \vec{D}_j^{\perp} = \sigma \tag{4}$$

$$\vec{B}_i^{\perp} = \vec{B}_j^{\perp} \tag{5}$$

where $\vec{J}$ and σ are the free current density and free charge density on the interface between media i and j, respectively. The superscripts $\shortparallel$ and $\perp$ stand for the components of the field parallel and perpendicular to the interface. The tangential and normal components of field must be continuous across the interface in case where there is no free charge or current. The relation between polarization and angle of incidence of e.m. waves are related by the interface matrix that is same for TE and TM modes at a normal incidence, but different at an oblique incidence.

2.1.1.1. The interface matrix for TE polarization. Following Fig. 2, it shows the TE polarization between two medium i and j. In i medium, we considered that E_i^+ and E_i^- are the incident and reflected waves, and E_j^+ and E_j^- are the transmitted and reflected waves in j medium. And H_i^+, H_i^-, H_j^+ and H_j^- are the related magnetic fields in i and j media and k_i^+, k_i^-, k_j^+ and k_j^- are the related propagation constants and θ_i, θ_j are the incident angles in i and j media, respectively.

Since the boundary conditions in Eq. (4), i.e., $\vec{D}_i^{\perp} - \vec{D}_j^{\perp} = \sigma$ hold in TE mode gives

$$E_i^+ + E_i^- = E_j^+ + E_j^- \tag{6}$$

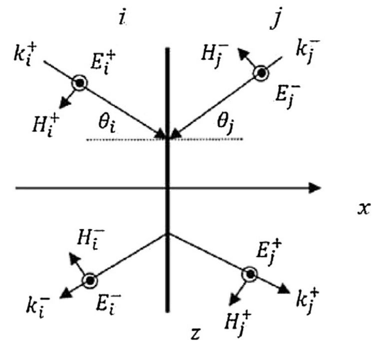

Fig. 2. Schematic diagram of the interface for TE polarization.

$$(H_i^+ - H_i^-)\cos\theta_i = (H_j^+ - H_j^-)\cos\theta_j \tag{7}$$

$$(H_i^+ + H_i^-)\sin\theta_i = (H_j^+ + H_j^-)\sin\theta_j \tag{8}$$

Here, $H = \sqrt{\epsilon/\mu}E$, $\epsilon = \epsilon_0\epsilon_r$ and $\mu = \mu_0\mu_r$ and where ϵ_0 and μ_0 are the free-space permittivity and permeability, and ϵ_r and μ_r are the relative permittivity and permeability of the medium. In case of non-magnetic and homogeneous media $\mu_r = 1$ and $\epsilon_r = n_r^2$, where n_r is the refractive index of the medium.

Using boundary condition $\vec{D}_i^{\perp} - \vec{D}_j^{\perp} = \sigma$ in Eqs. (6)–(8), then

$$E_i^+ + E_i^- = E_j^+ + E_j^- \tag{9}$$

$$(E_i^+ - E_i^-)\eta_i = (E_j^+ - E_j^-)\eta_j \tag{10}$$

where $\eta_v = \sqrt{\epsilon_v/\mu_v}\cos\theta_v = (\eta_v/Z_0)\cos\theta_v (v = i, j)$, and the free space impedance $Z_0 = \sqrt{\mu_0/\epsilon_0}$.

On solving Eqs. (9) and (10), we find a interface matrix for TE polarization as

$$\begin{bmatrix} E_j^+ \\ E_j^- \end{bmatrix} = M_{i,j}^{\mathrm{TE}} \begin{bmatrix} E_i^+ \\ E_i^- \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 + \dfrac{\eta_i}{\eta_j} & 1 - \dfrac{\eta_i}{\eta_j} \\ 1 - \dfrac{\eta_i}{\eta_j} & 1 + \dfrac{\eta_i}{\eta_j} \end{bmatrix} \begin{bmatrix} E_i^+ \\ E_i^- \end{bmatrix} \tag{11}$$

This equation is also called dynamical matrix or interface matrix for TE-polarization.

2.1.1.2. The interface matrix for TM polarization. Fig. 3 shows the boundary between media i and j for TM polarization. Now, the boundary condition $[\vec{B}_i^{\perp} = \vec{B}_j^{\perp} = 0]$ automatically holds, and also

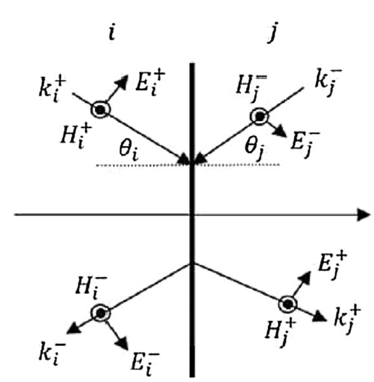

Fig. 3. Schematic diagram of the interface matrix for TM polarization.