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Double Resonance Characteristic of Photonic Crystal Structure with Defect Metal Layer

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ABSTRACT

The optical response of the photonic crystal structure has been analyzed using the Finite Difference Frequency Domain (FDFD) method. Simulation using this method aims to analyze the characteristics of light transmission when interacting with related structure. The results of the study of photonic crystal structures with two defects show that there are two transmittance bands called double resonances at two specific wavelengths. Changes in the resonance peak with respect to the variations of refractive index in the second defect layer resulted in a linear change with significant sensitivity. For photonic crystals with two defects, the first defect is a metal layer and the second defect is material sensing, which produces double resonance with a sensitivity of 7,825 and 3,2675, while for photonic crystals with the first defect, a dielectric layer, and the second defect is material sensing, produces single resonance with a sensitivity of 2,022. The choice of the first defect is that the metal layer is quite important, in addition to producing greater sensitivity, it also produces a field enhancement between the dielectric and the metal layer which is called surface plasmon resonance (SPR). The sensitivity value can also be set by determining the thickness of the second defect layer. These results can be used as a standard for fabrication and developed for sensor applications.

1. Introduction

The interaction of light with layered dielectric structures is an object that will continue to be studied because many phenomena can be applied to optical devices [1]. Analytical methods are built to see the optical characteristics of structures, such as transfer matrices and green tensors, but there are complexities in the problem of solving differential equations and forming geometries [2,3]. So, some researchers used many numerical methods to make it easier, more flexible and more efficient. Several numerical methods have been developed to analyze the interaction of light with periodic dielectric structures, including Finite Difference Frequency Domain (FDFD) [4]. FDFD is suitable because all materials have a frequency and permeability that depends on frequency, has the

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advantages of small cumulative error, and flexibility for modeling the effect attenuation [5]. Simulations of layered dielectric structures using the FDFD methods have evolved to layered metal-dielectric structures. The metal-dielectric structure has unique properties due to the presence of surface plasmon phenomena between the metal surface and the dielectric [6]. The plasmon surface is the free electron dense oscillation on the metal surface in contact with the dielectric material. Coupling of surface plasmon with electromagnetic fields around metal-dielectric surfaces give rise to surface plasmon polariton (SPR) [7]. The SPR phenomenon has been widely studied in the THz frequency range for the design of nanostructures such as prisms, fibers, gratings, and photonic crystal rods [8-11].

This study deals with numerical simulations of the interaction of light on photonic crystal structure using the FDFD method. Photonic crystal design uses a layered dielectric material that is inserted with two defects. The first defect uses metal, while the second defect can be changed as a sensing index. The metal-dielectric structure has been previously analyzed and shows the enhancement of transmittance due to the SPR phenomenon [12]. The FDFD method is used to analyze the field that comes out of the structure (transmission) which can be calculated to see the characteristics of the material. The use of metal materials as the first defect can be compared with dielectric materials related to changes in the transmittance peak to changes in the refractive index of the second defect material. These results can be developed for sensor devices that detect objects at a specific wavelength.

2. Methodology

2.1 Material Design

Photonic crystals (PC) are periodical optical micro- and nanostructures that receive increasing attention due to their ability to manipulate light propagation while maintaining high transmission efficiency [13]. If electromagnetic waves propagate into the photonic crystal structure, then the waves will be scattered due to differences in the refractive index in the structure. If the wavelength is much greater than the lattice constant of the PC, the structure behaves like an effective medium, but if the wavelength is proportional or smaller than the lattice constant of the PC there will be a Bragg reflection, thus forming a photonic band-gap in each boundary field of two different dielectric materials [14]. Important properties of photonic crystals can be obtained if there are defects in the photonic crystal structure. These defects cause localization around the band gap so that only transmittance will occur at one or certain frequency intervals which can be referred to as resonant bands [15]. Resonant bands at a certain wavelength have been used for optical devices, such as sensors and biosensors [16,17]. The characteristics of the resonance are determined by the characteristics of the defect layer in the photonic crystals namely the refractive index. The use of defects with metal materials can increase the transmittance of resonance because there is a coupling of a surface plasmon with electromagnetic fields around the metal-dielectric surface.

The corresponding the one dimensional PC we consider consists of regular cells of alternating dielectric and two defect cells with its structure as shown in Figure 1 with n_1 and n_2 denotes the refractive index of regular cells and their thicknesses are denoted by d_1 and d_2. The two defect cells are denoted by n_{d1} and n_{d2} with the related thicknesses are d_{d1} and d_{d2}. The number of regular cells on the photonic crystal structure is 20 layers with two layers of defects inserted inside. The following parameter values: $n_1 = 2.21\left(SiO_2\right)$, $n_2 = 3.61\left(GaAs\right)$, and the optical thicknesses satisfying the quarter wave stack condition: $n_1 d_1 = n_2 d_2 = \frac{\lambda_0}{4}$. The operating wavelength $\lambda_0 = 200\mu m$ so that $d_1 = 22.62\mu m$

and $d_2 = 13.85\mu m$. The two defect cells are chosen to be identical, with $d_{d1} = d_{d2} = 57.14\mu m$ and $n_{d1} = 0.27732 + 2.9278i$. The refractive index of the second defect n_{d2} is a material value that can be varied as the sensing index. This simulation was performed by using a plane wave. In the simulation we defined our computational boundary by imposing a perfectly matched layer (PML). Inside the PML area, the magnetic and electric conductivity are arranged so that there are no reflection effects in the computational boundary.

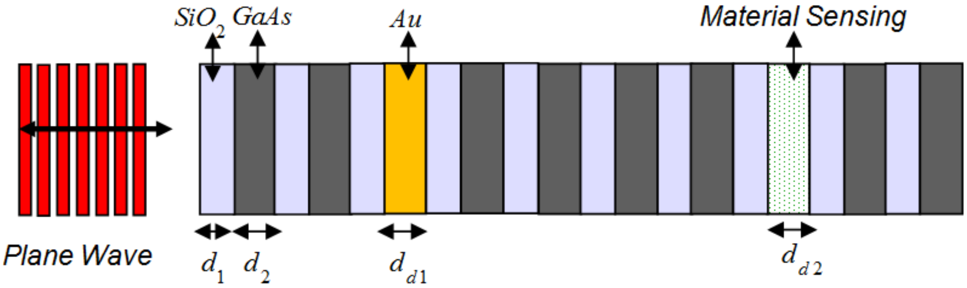


Fig. 1. Photonic crystal structure

2.2 Finite Differential Frequency Domain Formulation

The Finite Difference Frequency Domain (FDFD) method is a numerical solution for electromagnetic and acoustic problems, based on the Finite Difference approximation in the derivative operators of differential equations to be solved. This method can be applied to structures for any scale and any frequency of electromagnetic wave (EM) radiation. Maxwell's discretization into large system of linear equations conceptually simpler to understand and easier to implement than other methods, such as: finite element method and method of moments. The FDFD method is one of the most effective methods for obtaining the frequency responses of specific optical components [18].

The starting point of the FDFD method is the Maxwell equation in differential form, which can be discretized in the form, electric transverse magnetic (TM) or transverse electric (TE). For the case of a TM wave where the magnetic field $H(x,y)$ lies in the $x-y$ plane and the electric field $E(x,y)$ lies in the z plane, the discretization Maxwell's equations are given as follows:

$$\frac{\partial E_y}{\partial x'} - \frac{\partial E_x}{\partial y'} = \frac{E_y^{i+1,j} - E_y^{i,j}}{\Delta x'} - \frac{E_x^{i,j+1} - E_x^{i,j}}{\Delta y'} = \mu_{zz} H_z \tag{1}$$

$$\frac{\partial H_z}{\partial y'} = \frac{H_z^{i,j} - H_z^{i,j-1}}{\Delta y'} = \varepsilon_{xx} E_x^{i,j} \tag{2}$$

$$-\frac{\partial H_z}{\partial x'} = \frac{H_z^{i,j} - H_z^{i-1,j}}{\Delta x'} = \varepsilon_{yy} E_y^{i,j} \tag{3}$$

ε and μ are the electrical permittivity and magnetic permeability. Substitute Eq. (2) and Eq. (3) into Eq. (1) in the form of a homogeneous matrix equation, namely:

$$\left(\mathbf{D}_x^H \mu_{yy}{}^{-1} \mathbf{D}_x^E + \mathbf{D}_y^H \mu_{xx}{}^{-1} \mathbf{D}_y^E + \varepsilon_{zz}\right) \mathbf{E}_z = 0 \tag{4}$$

This equation will produce a trivial solution if the source $\mathbf{b}$ is included, which converts the matrix equation to the form $\mathbf{A}$

$$\mathbf{A}\mathbf{E}_z = \mathbf{b} \tag{5}$$

Using the total-field/scattered-field formulation, source can be defined as:

$$\mathbf{b} = (\mathbf{Q}\mathbf{A} - \mathbf{A}\mathbf{Q})\mathbf{f}_s \tag{6}$$

The masking function has 1's at each point on the grid that corresponds to positions in the scattered-field and 0's at each point that corresponds to the total-field.

$$\mathbf{Q} = \begin{pmatrix} 1 & & & & \\ & 1 & & & \\ & & \dots & & \\ & & & 0 & \\ & & & & 0 \end{pmatrix} \tag{7}$$

The matrix equation on the Eq. (5) can be solved for $\mathbf{E}_z$ to calculate the field

$$\mathbf{E}_z = \mathbf{A}^{-1}\mathbf{b} \tag{8}$$

and Bloch's theorem in periodic structures.

$$\mathbf{A}_{tm}(x) = \mathbf{E}_z(x, y_{tm})e^{\pm jk_x x} \tag{9}$$

k is the wavenumber. Finally, Transmittance values can be calculated through the following equation:

$$T = |S_{trn}|^2 \left(\frac{k_y^{trn} \, \varepsilon_{r,trn}}{k_y^{inc} \, \varepsilon_{r,inc}} \right) \tag{10}$$

where k_y^{trn} and k_y^{ref} is longitudinal component, the wave vector on the grid varies and is calculated through the dispersion relation.

3. Results

The photonic crystal model in Figure 1 is simulated using FDFD method with the specifications above described. Two layer defects can be seen in the simulated structure in Figure 2, namely the first defect is metal material and the second defect is sensing material. For the numerical calculation, we consider the number of mesh to be 118×704 with the size is $dx = dy = 53\mu m$.

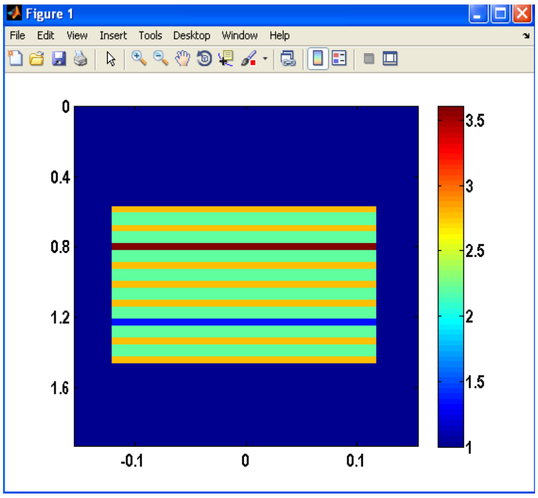
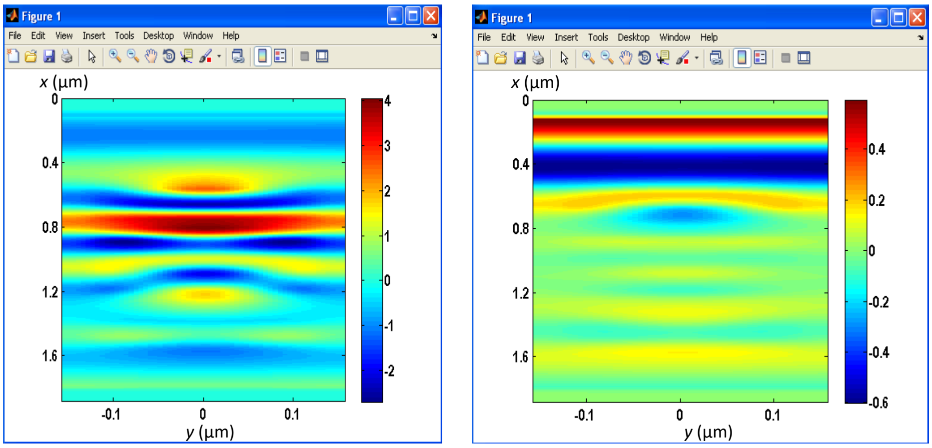


Fig. 2. Simulation model on the photonic crystal

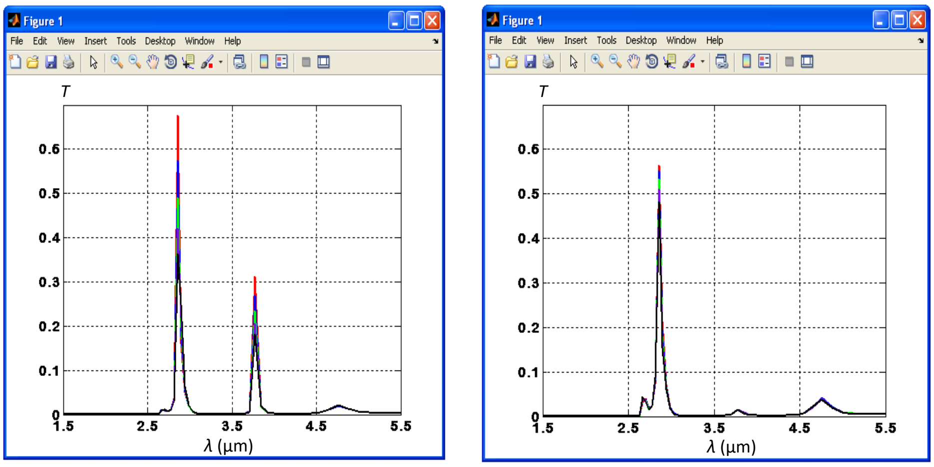
When the electromagnetic wave interacts with the photonic crystal structure, it can be seen that the field enhancement in the first defect is a metal material (Figure 3(a)). The field enhancement occurs at a frequency $1.5THz$ which is the resonant frequency between the frequency of the electromagnetic wave and the natural frequency of the electrons in the metal. The simulation results show that there is an SPR phenomenon that can be analyzed on the characteristics of resonance band according to the change in refractive index in the second defect. For other frequencies, there is no field increase in the defect layer as shown in Figure 3(b).



(a) (b)

Fig. 3. Electric field distribution in PC at frequency: (a) $1.5THz$ and (b) $2THz$

The simulation results show changes in the transmittance peak of resonance band according to changes in the refractive index of the material at the second defect. At the refractive index value: 1.30 (red), 1.31 (blue), 1.32 (green), 1.33 (purple), and 1.34 (black). It can be seen that the change in the transmittance peak of resonance band for the photonic crystal structure with the first defect is the metal layer (Figure 4(a)) is more significant than the photonic crystal structure with the first defect is the dielectric layer (Figure 4(b)). For photonic crystal structure the first defect is the dielectric layer, producing a single resonance at the wavelength $2.850\mu m$. This is in accordance with previous studies that when the number of layers meets $N = M + L$, it will produce a single photonic band-pass at one wavelength, whereas for the photonic crystal structure with the first defect is a metal layer producing two photonic resonances at wavelength $2.875\mu m$ and $3.750\mu m$ [20].



(a) (b)

Fig. 4. Response of resonance band (a) double resonance or PC with first defect metal (b) Single resonance PC with first defect dielectric

The changes in peak transmittance at double resonance for the changes in refractive index of second defect 1.30 to 1.34 can be seen in the simulation in Figure 5. For the first resonance at wavelength $2.875\mu m$ (blue) the result is more linear than the second photonic resonance at wavelength $3.750\mu m$ (red).

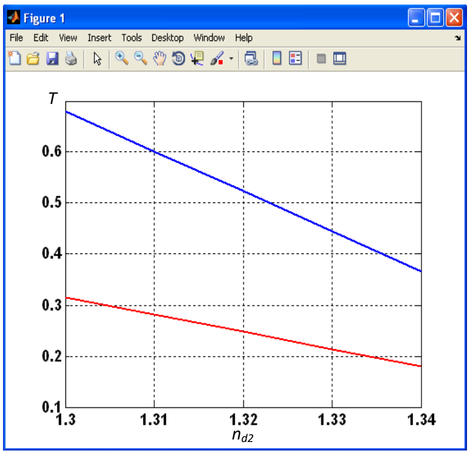


Fig. 5. Plot of first resonance peak (blue) and second resonance peak (red) respect to refractive index of second defect

The sensitivity of the output response can be defined as the ratio of the value of the change in transmittance to the change in the refractive index in the defect layer

$$S = \frac{dT}{dn_{d2}} \tag{11}$$

For the simulation results in Figure 4, the sensitivity can be calculated, namely 7.8425 for resonance band at wavelength $2.875\mu m$ and 3.2675 for resonance band at wavelength $3.750\mu m$.

To compare the sensitivity of resonance band at a wavelength $2.875\mu m$ for a PC with metal defects and photonic band-pass at wavelength $2.850\mu m$ for a PC with a dielectric defect, see the simulation results in Figure 6. The resulting sensitivity respectively is 7.8425 and 2.022.

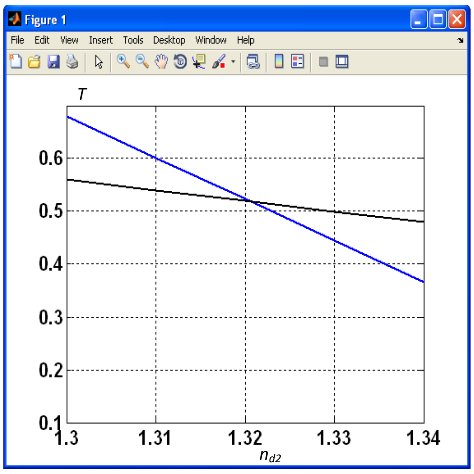


Fig. 6. Plot of resonance peak respect to refractive index for: PC with first defect is metal layer (blue) PC with first defect is dielectric layer (black)

The sensitivity response can be adjusted by selecting the thickness of the second defect layer which is the sensing index layer. If the thickness of the second defect layer is smaller, the sensitivity is greater. In the simulation results in Figure 7, resonance peak vs. refractive index produces a sensitivity of 10.7225 (red), 7.8425, (blue), 5.31 (black) with the thickness of the second defect layer as successively: $54.05\mu m$, $57.14\mu m$, $60.60\mu m$. The value of the thickness of the second defect layer is limited to a minimum $\frac{\lambda_0}{4}$ or equivalent of $50\mu m$.

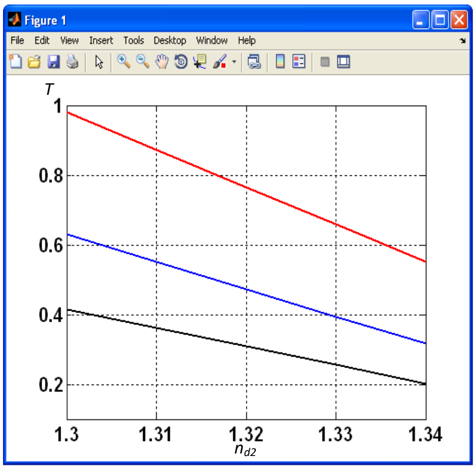


Fig. 7. Plot of resonance peak respect to refractive index the second defect with the thickness of the second defect layer as successively: $54.05\mu m$ (red), $57.14\mu m$ (blue), $60.60\mu m$ (black)

4. Conclusions

The simulation results using the FDFD method for photonic crystal structures with two defects, resulting in a more linear response to changes in transmittance peaks for photonic crystals with the first defect using metal materials. For photonic crystals with two defects using metal, one of them produces a double resonance at wavelengths $2.875\mu m$ and $3.750\mu m$. The first resonance is more sensitive than the second resonance. The sensitivity value in response to changes in the PPB peak to the refractive index of the second defect can be adjusted by determining the thickness of the layer of he second defect, which is smaller than $50\mu m$.

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