Investigation of different parameters in defective photonic crystal

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Abstract—In this paper we will investigate the properties of photonic band structures in one dimensional photonic crystal by using transfer matrix method. We have obtained the tenability of the different parameters in one-dimensional defective photonic crystal. In our calculation we have used Lithium Tantalate ($LiTaO_3$) as a defect layer to study the tunability of photonic crystals by applying external voltage. The numerical result show that the defect peak is blue shifted as the positive bias is applied, whilst it red shifted by applying the negative bias voltage. The relation is straight line between external applied voltage and defect peak. Moreover, the temperature tuning is achieved by changing the defect layer to be (NOA61), the defect peak is red shifted by increasing temperature. These characteristics can be used on tunable filters, voltage and temperature sensors.

Keywords—Photonic crystal, voltage tuning, defect mode, transmittance

1. Introduction

Photonic crystals (PCs) are periodic, dielectric, and composite structures in which the interfaces between the dielectric media behave as light scattering centers. In general, PCs can be classified into three types, i.e., the one dimensional(1D),the two dimensional(2D) and the three dimensional (3D) PCs [1-9]. The common properties among these three types of PCs are the appearance of forbidden frequency regions or the so called photonic band gaps (PBGs) and photon localization [10, 11]. The PBG means that electromagnetic waves of certain frequencies cannot propagate in any direction in the PC due to Bragg scattering at the inference in this periodic structure. The appearance of these PBGs is strongly depending on the constituent materials of the PCs. Using appropriate constituent materials, the PBGs can be altered and thus a tunable PC can be obtained. Wherein, the photon localization presents the possibility to make some discontinuous electromagnetic waves peaks in the PBG due to the presence of disorders within the structure. With the addition of defect layer, the resonant transmission peaks or the defect modes can be generated within the PBG [12-14]. Based on the tuning agent, it is possible to design and fabricate PCs for various applications in optoelectronic and microwave devices such as optical modulators, switches, tunable filters, and tunable resonators [15]. The tunability of PCs is strongly depending on the modification of the permittivity or/and the permeability of one of the constituent materials by some external parameters such as; external electric field [16, 17], applied magnetic fields [18–20], temperature [21], hydrostatic pressure [22], and the operating temperature of superconducting materials [23-25].

In this paper, we investigate theoretically the tunable properties of a 1D defective PC depending on the effect of some external parameters on the defect layer such as an external applied electric voltage, and temperature variations. The impulsion around studying these tuning features over than the others returns to their simplicity in applications and stability. In addition, we demonstrate the response of the transmission spectrum under the incident angle variation in the presence of the external electric voltage. Here, we consider our structure to be $(AB)^5D(AB)^5$, where A,B and Dare high, low refractive index material and the defect layer, respectively. Our calculation method is based on the transfer matrix method (TMM). The numerical results show that the external applied voltage has a tremendous effect on the properties of the defect modes over the temperature variations. The applied electric voltage leads the defect peak to blue shifted as the positive bias is applied, whilst it red shifted at negative bias voltage. This paper is organized as follows: in Sec. 2, we discuss the basic equations and the structure description. In sec. 3, we present the results and discussion. The conclusions are summarized in Sec. 4.

2. Basic equations

Let us consider a defect layer immersed between two identical periodic structures, each of them represents a perfect 1DPC as shown in Figure (1).

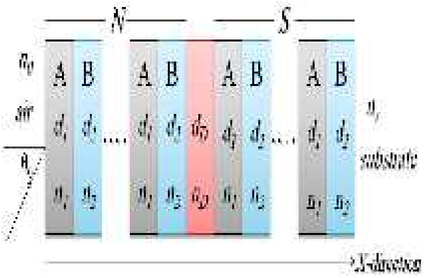


Figure (1):- A defective 1D PC structure, in which the thicknesses of the dielectric layers are

The first periodic structure is repeated for *N* times, while the second is repeated for *S* times, where *N* and *S* are integers. Both the structures are made of two dielectric materials denoted by A and B. d_1, d_2 and n_1, n_2 are the thicknesses and the refractive indices of the dielectric layers A and B, respectively. The refractive index and the thickness of the defect layer are denoted by n_D and d_D, respectively. The whole structure is situated between vacuum and a substrate [14]. The refractive index of the defect layer ($LiTaO_3$) is depending on the external electric field and the wave length of the incident electromagnetic wave which can be described as follow[26]:-

$$n_e' = n_e - \left(\tfrac{1}{2} n_e^3 \text{¥}_e E\right), \qquad (1)$$

where, ¥_e is the electro optical coefficient, and *E* is the electric field strength that can be calculated by [27]:-

$$E = \frac{V}{H}, \qquad (2)$$

Where, *V* is the applied electric voltage and *H* is the height of the sample. Then n_e is depending on the wave length as follow:-

$$n_e = n_e(\text{a}) = \left(4.5820 - \frac{0.099169}{0.044432 - \text{a}^2} - 0.021950\,\text{a}^2\right)^{1/2}$$

. (3)

Finally in order to include the effect of temperature on the defective 1D PCs. It is well known that the thickness and refractive index of medium can be changed due to the thermal-expansion effect and thermo-optical effect [21]. The changes in the thicknesses of the constituent materials due to temperature can be expressed as,

$$d = d_o + \sim d_o \Delta T \,. \qquad (4)$$

Where, d_o is set to be the thickness at T = 298 K and ~ are the thermally linear expansion coefficient. Then, the refractive indices are dependent on temperature according the thermo optical effect as follows:

$$n = n_o + \quad n_o \Delta T, \qquad (5)$$

Where, n_o is the refractive index of Si at room temperature and β is the thermo-optic coefficient. Now, we will study the electromagnetic waves interaction within this multilayer structure by using the TMM which given by [27-29]

$$M = D_0^{-1}\begin{pmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{pmatrix}\begin{pmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{pmatrix}\begin{pmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{pmatrix} D_s =$$

$$\left(D_0^{-1}\left(\prod_{l=1}^{N} D_l p_l D_l^{-1} D_{l+1} P_{l+1} D_{l+1}^{-1}\right)\left(D_d P_d D_d^{-1}\right)\left(\prod_{l=1}^{N} D_l P_l D_l^{-1} D_{l+1} P_{l+1} D_{l+1}^{-1}\right) D_s \right)$$

(6)

Where (D) is the dynamical matrix and (p) is the propagation matrix which can be written as:-

$$D_l = \begin{pmatrix} 1 & 1 \\ n_l \cos\text{−}_l & -n_l \cos\text{−}_l \end{pmatrix} \quad \text{For TE waves}$$

$$D_l = \begin{pmatrix} \cos\text{−}_l & \cos\text{−}_l \\ n_l & -n_l \end{pmatrix} \quad \text{For TM wave}$$

The propagation matrix in the form of sine and cosine:

$$p_l = \begin{pmatrix} \cos\text{¤}_l + i\sin\text{¤}_l & 0 \\ 0 & \cos\text{¤}_l - i\sin\text{¤}_l \end{pmatrix}$$

At [i=1,2,3,…..]

Where $\text{¤}_l = \dfrac{2\text{®}\, d_l}{\text{a}} n_l \cos\text{−}_l$

The transmittance *T* and reflectance *R* are determined by following expression

$$R = |r|^2 = \left|\frac{M_{21}}{M11}\right|^2,\ T = |t|^2 = \left|\frac{1}{M11}\right|^2 \quad (7)$$

3. Results and discussion

In this section, we present the numerical results of the electromagnetic waves propagation in our structure under the effect of both the applied electric voltage and the temperature variations. Our structure is designed using two different dielectric materials, i.e., the first one (A) is Si which is a lossless material with a constant index of refraction, n_1=3.45, whereas the second material (SiO_2) with n_2=1.45 [30]. In addition, we choose $LiTaO_3$ which acts as an electro-optical material as a defect layer to study the effect of the external electric voltage. In the other hand, we use NOA61 to study the effect of temperature variations on the characteristics of the defect mode. Then, all layers arrest to be triple quarter-wavelength, i.e., n_Ad_A= n_Bd_B= n_Dd_D=3 (λ_0/4) with a design wavelength of λ_0=600nm.Thesubstrateistakentobeglass with a refractive index of n_s=1.52.Moreover, we used N=S=5, so the total number of the periods is10. The results section is divided into two subsections. Firstly, we obtain the effect of the applied voltage on the position and the intensity of the defect mode. Secondly, we investigate the dependence of the defect mode on the temperature variations.

3.1.Defect mode dependence on the applied voltage

In this subsection, we concentrate on studying the effect of the applied electric voltage on the defect mode properties. In figure (2), we plot the normal incidence transmittance spectra versus the wavelength for 1D defective PCs when the applied voltage is zero. As shown in figure(2), the PBG appears in the visible region with bandwidth=666-550=116nm. Moreover, the presence of $LiTaO_3$acting as a defect layer leading to the appearance of a narrow peak with high transmittance equal to 0.5 at the design wavelength of 594nm owing to the breaking of the periodicity. Also, the transmittance response outside the PBG is affected by the some fluctuations due to the existence of the defect layer.

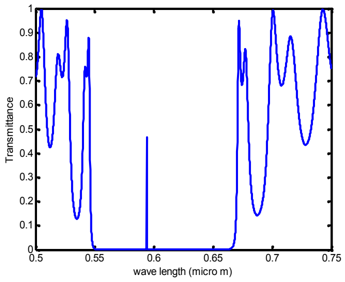


Figure (2):- Transmittance spectra of 1D PCs contain electro

Next, we investigate the defect mode properties under the influence of the electric voltage. In figure (3), the transmittance is plotted as a function of the wavelength at different values of the applied voltage. Here, we choose the height of the defect layer (H=0.4mm). We observe that the defect mode is strongly affected with the applied voltage variations. As the applied voltage increases from 0V to 20 KV, the defect mode is shifted towards the UV frequency regions. This effect is still presenting the further increment in the applied voltage values. This response makes the PCs very promising in many applications such as tunable filters and voltage sensor.

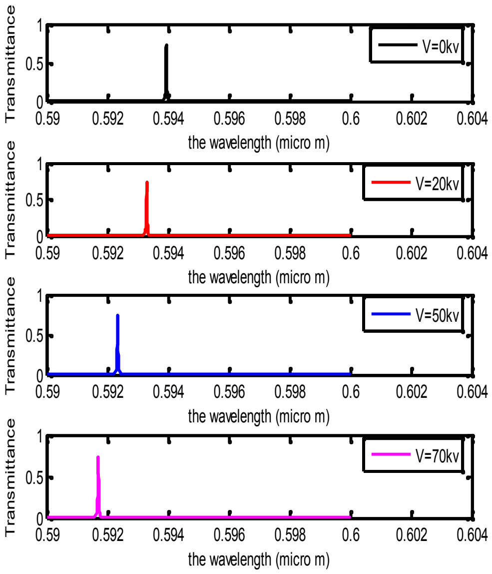
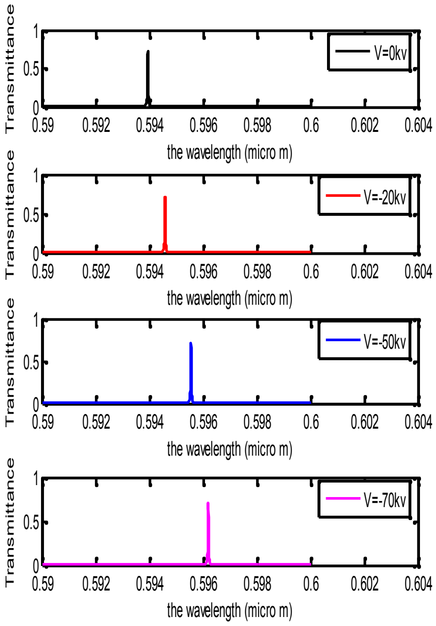


Figure (3):-Transmittance spectra for defect peak inside the photonic band gap at different positive applied voltage, v=0, 20, 50, and70 KV, respectively.

In the other hand, we study the defect mode properties for the negative bias voltage. Figure (4), shows that the defect mode is red shifted toward the near infrared as the voltage values increase in the negative direction. Then, figure (5) describes the tunability through both positive and negative voltage.



Figure(4):- Transmittance spectra for defective PC when we apply different negative bias voltage at V=0,-20,-50, and -70KV, respectively.

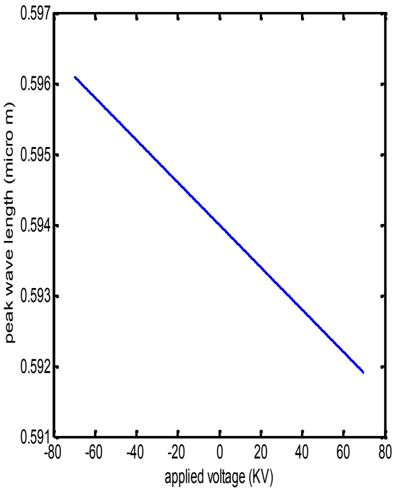


Figure (5):- Relation between the defect peak wave length and the applied voltage which taken from (-80 to 80KV).

3.2. Defect mode dependence on the temperature

Finally, we demonstrate the dependence of the defect mode on the temperature variations. Here, we set the thermal expansion values for Si, SiO_2, and NOA61 as $2.6\times10^{-6} K^{-1}, 5.5\times10^{-7} K^{-1}, \text{and } 220\times10^{-6} K^{-1}$ [28], respectively. Moreover, the thermo-optic coefficient for Si, SiO_2, and NOA61 are $1.86\times10^{-4} K^{-1}, 1\times10^{-5} K^{-1}, \text{and } 1.85\times10^{-4} K^{-1}$, [28] respectively. Whereas, the refractive index of NOA61= 1.56, and thicknesses of A, B, D are equal to quarter wave length $n_A d_A = n_B d_B = n_D d_D = \lambda_0/4$. Figure (6) shows the transmittance spectra at different temperature degrees T= 298^0K, 320^0K, 380K, and 450^0K.It is seen that the defect mode inside the PBG is shifted toward higher frequency regions. This effect may due to the changes in the refractive index and thickness of the constituent materials as the variation in the temperature values. Furthermore, table (1) shows the wave length shifting by increasing the temperature. From this result, temperature tuning is accomplished successfully which can be used in the design of thermally tunable narrowband transmission filter.

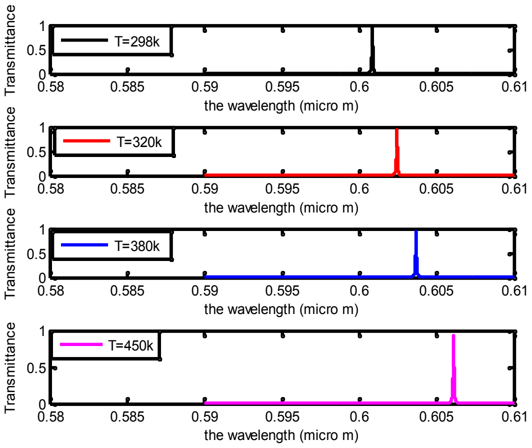


Figure (6):- Transmittance spectra for defective PC at different temperature at T=298K, 320K, 380K, and 450K, respectively.

Temperature	λ_p(nm)
T=298K	600nm
T=320K	602nm
T=380K	604nm
T=450K	606nm

Table (1):- The positions of defect mode due to the temperature variations.

4. Summary

Based on the TMM, we theoretically investigated the tunability of 1D defective PCs using external applied Voltage, and temperature variations. We used an electro optical material as a defect layer ($LiTao_3$), thus its refractive index changes with changing the external applied voltage. The numerical results demonstrated that, the defect peak is blue shifted by increasing the positive bias voltage and red shifted by increasing the negative bias voltage. Moreover, we used (NOA61) to study the effect of temperature on the defect mode properties. This type of tuning indicates that, the defect mode can be shifted toward the near infrared regions. Among the tuning features studied in this paper, the applied voltage tuning has the advantage over the temperature tuning. It has the ability to verify tenability at high and low frequency regions. Our structures are good candidates for many optical devices, such as tunable filters, sensors, voltage sensors, and temperature controlled optical shutters among photo-electronics applications.

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