Optical Band Gap Engineering based on Single and Multiple Twin Defects Distribution inside One-dimensional Photonic Crystals

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Summary
In this paper band gap tuning for one-dimensional photonic crystals by introducing single or multiple twin defects is investigated. We show that by use of the width and index of refraction of introduced defect layers the reflected and transmitted bands can be controlled. It is shown that introduced defect layers convert some part of the reflection band to transmission band. Also, we show that using multiple defects, number of peaks and holes in the reflected and transmitted signals can be controlled. In this study it is shown that distance between defects is important for band gap engineering. Also, using the proposed method, tunable optical multi-band filters can be designed that is so important for optical signal processing. The proposed technique can be realized using electro optics and all optical methods.

Key words:
Photonic Crystals, Band Gap Engineering, Array of Defects

1. Introduction

Optical techniques and methods are interesting for general engineering applications and especially computing and communication purposes. High-speed communication and processing is realized by optical fiber based methods. In starting of optical techniques to enter into engineering applications the mixed cases were considered. For example, in optical communication, modulation and detection are strongly related to electrical methods. Also, in repeaters first optical signal is converted to electrical and amplified in electrical domain and then it is converted to optical signal and finally transmitted again.

Nowadays conversion to electrical signal is one of basic problems that introduce more delay and low speed of communication and processing is result of this conversion. Nowadays industrial and biological applications strongly require high speed processing and communication methods. For this purpose all optical method is one of suitable alternatives. Also, realization of different applications in compact form such as optical integrated circuit is so interesting. As in electronic integrated circuit that single crystals had critical role, in optical integrated circuit case, photonic crystals have important role.

Recently, photonic crystals have attracted much attention from both fundamental and practical point of views, because novel concepts such as photonic band gaps have been predicted and various new and interesting applications of photonic crystals have been proposed [1]-[3]. Also, localization of light and the controllable inhibition of spontaneous emission of light are most important applications. For applications in optical devices and systems, it is important to realize the tunability of photonic crystals that is to control photonic band structures such as photonic band gaps. Therefore, tunable photonic crystals composed of materials whose properties can be changed by adjusting external factors have been proposed [4], [5]. In this direction, electro-optical Pockels effect was used for temporal modulation and tuning of photonic crystals [6].

Introducing defects in photonic crystals is another method for controlling of optical characteristics of photonic crystals. Effect of defects on optical properties of photonic crystals is discussed in this paper and was discussed in other aspects for single defect layer in [6].

In this paper, we investigate effect of single and multiple (or array of defects) defects on optical properties (band gap variation, which is illustrated in the reflection and transmission coefficients) of one-dimensional photonic crystals. Here, using number of twin defects introducing number of peaks in frequency domain can be controlled. Also, using the prepared idea really multi-band optical filters easily can be proposed without superimposing that is hard for implementation. In this work, we obtain optimum values for defect parameters from system operation point of views.

Organization of this paper is as follows. In section II mathematical modeling based on the Transfer Matrix Method (TMM) is introduced. Simulation result is discussed in section III. Finally the paper ends with a conclusion.

2. Mathematical Modeling

Fig. (1) shows one-dimensional photonic crystal including multiple defect layers different from layer width and the index of refraction point of views. In this optical system the incident light is applied from left and the reflected wave and transmitted wave are shown in the following figure. Our case includes N layers periodic structure including defect layers from each N_1 layer. On the other hand between two defect layers there are N_1 periodic layers. Parameters of each defect layers are different generally in considered cases. In the following effect of defect layers based on TMM method on optical properties of one-dimensional photonic crystals is presented.

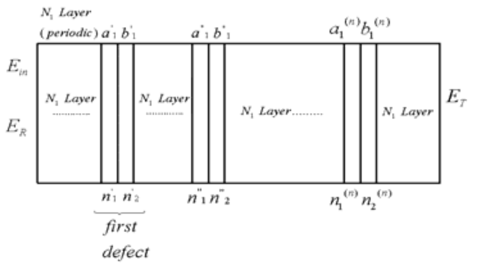

Fig. 1 Schematics of one-dimensional photonic crystal including multiple defects

Number of defect layers and layers parameters are used to manipulate the reflection and transmission spectral profiles. For derivation of spectral properties, the Transfer Matrix Method is used. Our analysis is concentrated on a system including 204 layers. Analysis considered different cases such as single, two, three and four twin defect elements. In these cases spectral profiles of the reflection and transmission coefficients are studied. For evaluation of the proposed ideas, TMM is used that is formulated as follows.

$$M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = D_0^{-1}\left[\prod_{l=1}^{N} D_l P_l D_l^{-1}\right] D_s, \quad (1)$$

where

$$\begin{pmatrix} A_0 \\ B_0 \end{pmatrix} = M \begin{pmatrix} A_s' \\ B_s' \end{pmatrix}, \quad (2)$$

where A_0 , B_0 , A_s' , and B_s' are electric field coefficients in first and last layers respectively. Also note that our calculations are in TE-mode of propagation and D, P and D^{-1} are dynamic propagation and inverse dynamic matrix that are related to boundary conditions. The introduced matrices for TE polarized field can be calculated as follows.

$$D_l = \begin{pmatrix} 1 & 1 \\ n_l \cos\theta_l & -n_l \cos\theta_l \end{pmatrix}, \quad (3)$$

$$P_l = \begin{pmatrix} e^{i\phi l} & 0 \\ 0 & e^{-i\phi l} \end{pmatrix}, \quad (4)$$

$$\phi_l = k_l d_l, \quad (5)$$

$$k_l = \sqrt{(n_l\, \omega/c)^2 - \beta^2}, l = 0,1,2,........., N, S \quad (6)$$

In the next section, different cases are considered and simulated results are illustrated.

3. Simulation Results

In this section based on the presented TMM method, the simulated results are presented and discussed. Fig. 2 shows the reflection coefficient versus input frequency for pure periodic case (without defects). As it is shown there is band gap that is illustrated in the figure and can be used as optical filter, which is used as traditional Bragg Grating blocks. The proposed periodic structure is optical filter and the bandwidth can be tuned by the index of refraction contrast and medium length also.

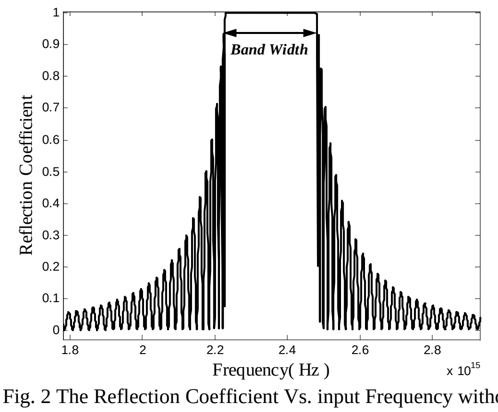

Fig. 2 The Reflection Coefficient Vs. input Frequency without defect layers

In the following effect of single twin defects on the reflection coefficient is demonstrated. As it is shown after introducing a single defect twin layers in center of the forbidden band (band gap) a controllable transmission band is going to be appeared. Fig. 3 illustrates that defect layers can change optical properties of photonic crystals strongly. Effects of two, three and four twin defect layers are illustrated in Figs. (4, 5, 6). As it was told introducing a twin defect layers generate a transmission band inside the band gap and the generated band characteristics can be controlled by parameters of the twin defect layers.

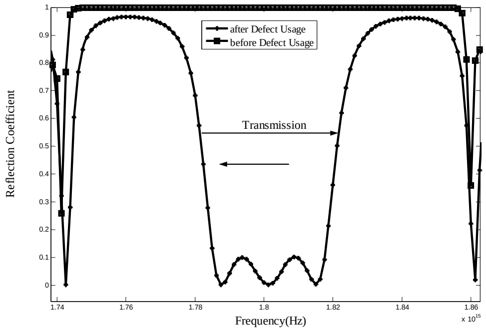

Fig. 3 The Reflection Coefficient Vs. input Frequency for single twin defect layers

Fig. 4 shows effect of two twin defect layers on optical properties of the proposed structure. We see that there are two reflection peaks and three transmission bands inside the reflection band or band gap. Duration of the transmission bands, bandwidths of the reflection bands and central frequency of the reflection bands can be controlled by tuning of parameters of the introduced defect layers.

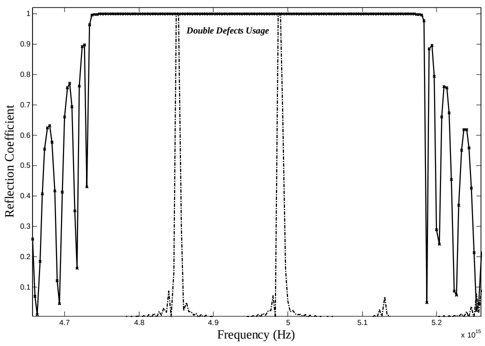

Fig. 4 The Reflection Coefficient Vs. input Frequency for two twin defect layers

By introducing a triplet twin defect layers, four transmission bands as well as three reflection peaks including tunable characteristics are generated.

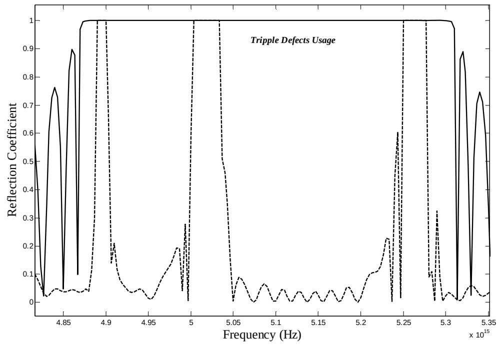

Fig. 5 The Reflection Coefficient Vs. input Frequency for Triple twin defect layers

Finally, for four twin defect layers, five transmission bands and four reflection peaks are introduced.

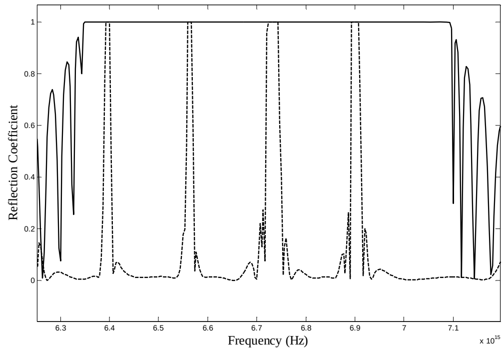

Fig. 6 The Reflection Coefficient Vs. input Frequency for Four twin defect layers

So, using an introduction of twin defect layers, band gap of the proposed structure can be engineered.
The effect of the length of the defect layers on the generated transmission bands for three cases is illustrated in Fig. 7.

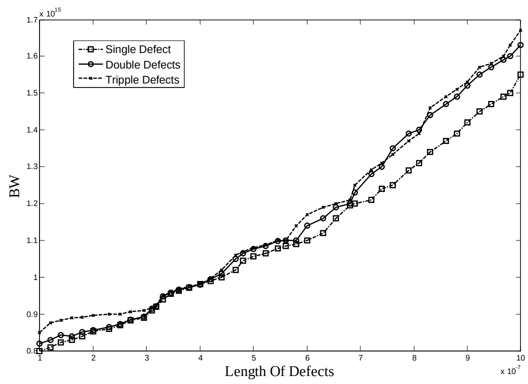

Fig. 7 Bandwidth of the generated bands Vs. length of the introduced defect layers

Correspondingly bandwidths of the appeared reflection peaks versus the index of refraction variation for three cases are illustrated in Fig. 8.

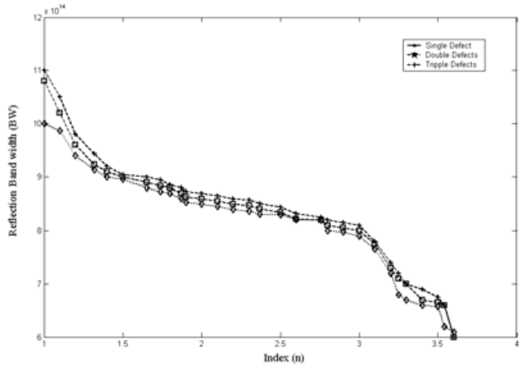

Fig. 8 The Reflection Bandwidths Vs. the index of refraction of the defect layers

The distance of minimum point of the appeared transmission band versus the length of twin defect layers for three cases is illustrated in Fig. 9.

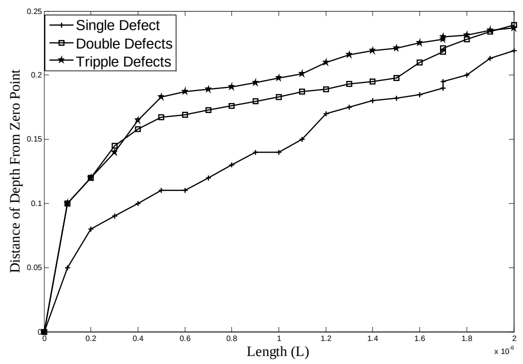

Fig. 9 Distance of Depth Vs. the length of the defect layers

Also, the mentioned above quantity is illustrated versus the index of refraction in Fig. 10.

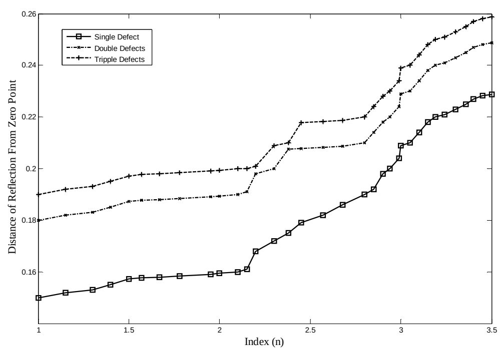

Fig. 10 Distance of Depth Vs. the index of refraction

Finally, the central frequency of the introduced transmission band versus the index of refraction is illustrated in Fig. 11.

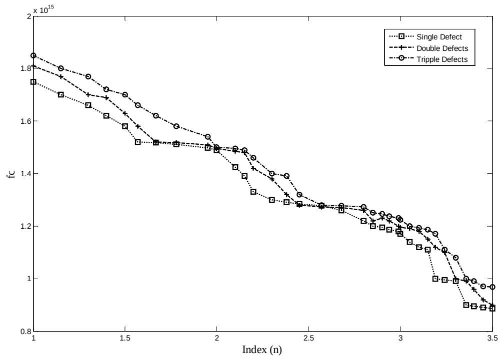

Fig. 11 Central Frequency Vs. the index of refraction of defect layers

Finally, the effect of distance between defect twin layers on transfer function is illustrated in Fig. 12.

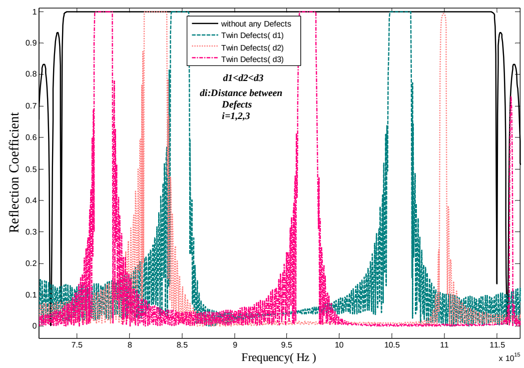

Fig. 12 The Reflection Coefficient Vs. input Frequency for different defect distances

Our simulations have shown that using introduced twin defect layers band gap engineering can be performed. By change of the index of refraction and distance between defect layers optical transmission and reflection bands can be controlled.

Conclusion

In this paper, band gap engineering based on introducing twin defect layers has been introduced. The proposed idea has been investigated by study of the effect of different parameters of defect layers on optical properties of the structure. The proposed technique can be used as an alternative for generation of multi-band optical filtering. Also, the effect of distance between defect layers has been studied in this paper. We have shown that distance between defect layers has critical effect on optical properties of the proposed structure.

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