Adjustable Filters For Optical Communications Systems Based On One-Dimensional Photonic Crystal Structures

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ABSTRACT

IN this paper design and simulation of all optical filters have been done by one-dimensional photonic crystal structures based on some materials like Silicon (Si) and Germanium (Ge). By using of Transfer Matrix Method (TMM), optical fiber with too narrow bandwidth is gained. Also the defect effect has been studied in frequency feature of filters and it has been showed that by replacing defects in suitable places of designed structure, bandwidth and central frequency face changes that we can regulate their parameters according to application type of filters. Also by increasing the number of layers, bandwidth of filter decrease. One of the most important advantages of this structure is having some passing-bands. Wave length limits of mooted structure are about one micrometer.

Keywords — transfer matrix method , photonic crystal , defect , filter , Bandwidth.

I. INTRODUCTION

Nowadays, modern networks of optical telecommunications are able to transfer voice and computer images and data with a speed that is one hundred times more than telecommunications networks with copper cables [1]. The process and alteration of optical signals into electric current is troublesome in high speeds, so if the width of optical pulses become less, the need to more expensive and complicated electronic circuits will increase that is difficult and costly. In this condition, the simpler, faster and more economic solution is complete transferring of optical signs from one point to another point that such all optical networks can be replaced with present optical fiber systems which have optoelectronic devices. Seeking photonic all optical networks technology is necessary in this situation [2],[3]. Photonic crystals of periodic structures are dielectric materials that optical waves (electromagnetic) can not pass them in special frequency spans, this section has been named photonic band gap **(PBG)** [4], [5], by photonic band gap engineering as defect, we can change their band structure [6],[7]. Also they have a main role in designing all optical devices as optical switches [8],

optical filters [9], optical multiplexers [10] and optical di-multiplexers [11].

Photonic crystal structures are designed in one-dimensional, two-dimensional and three-dimensional types [12]-[14]. Parameters as layers refractive index, distances among layers, layers number and their arranging method are all effective on the type of structure act [5]. To analyze these structures, various numerical methods like TMM [15], FDTD and other methods are used. In this paper, all optical filters design has been done by using of natural characteristics of photonic crystals in passing or reflecting light. Therefore the base of this paper is following levels:

At first, we discuss about the advantages of optical telecommunications systems and then design and simulation levels of considered structure are explained. After that we do essential simulation for structure and design narrow band filters, finally the results of study are presented.

I - 1) Advantages Of Optical Fiber telecommunications Systems

In brief, the advantages of optical telecommunications systems are presented as follows:

a) Having high bandwidth and transferring high volume of modulated information with optical fiber toward radio bands .
b) Having low dimensions and thickness and being isolator in comparison with metal cables for sparking and immunity against co-hearing and resulted effects of thunder .
c) Having too low casualties, high flexibility, cost and assurance coefficient in the action of optical fibers toward metal cables .

So most of today`s researches in optical telecommunications are about the most important development in manufacturing optical amplifiers.In this way beside power and amplifica-tion ,the need to alter optical signs is removed .Because they`re able to amplify digital data in speeds of multi hundred Giga bits per second and even multi Tera bits per second and amplify some different wave length simultan- eously . So the condition of optical multiplex and the wave width of system **(WDM)** let us to profit in more economic

form. For example, we can equip each radio transmitter to a changeable frequency laser and without image concision operation transmit a television program that have high clear images with band width of one Giga bit per second [16].

II. OPTICAL DETECTORS

In optical telecommunications systems, optical detectors sector has special importance and sensitivity. So in optical telecommunications systems, narrow band filters are designed by Dense Wavelength Division Multiplexing method (**DWDM**). Therefore we used defect technique for periodic networks to study the results of applied filter. So by using of transfer matrix method (TMM), frequency response of considered filter should be analyzed in wave length of $1.1\,\mu m$ to $1.6\,\mu m$. Indeed it is structure study of filters which are the forth generation of telecommunications fibers in optical communications systems classification (see Table 1). For more accurate study, simulated waves shapes and calculation conditions have been analyzed in $1.198\,\mu m$ to $1.2\,\mu m$.

Table 1. Range Communication Band

Band name	O Band	E Band	S Band	C Band	L Band
Wave length limit based on Nanometer	1260 to 1360	1360 to 1460	1460 to 1530	1530 to 1565	1565 to 1625

In Fig. 1 as we see, 500 layers in symmetrical form, from left to right have been considered with one pair of crystal Silicon and Germanium with refractive indexes of $n_{Ge}=4$ and $n_{Si}=3.45$. In the next level, the middle of structure from air distance with refractive index of $n_{air}=1$ has been used for enforcing defect (in this condition, because of symmetry, the number of layers is 501) , gradually the number of defect pairs is increased and finally the effect of graded index on the act of optical filter is studied.
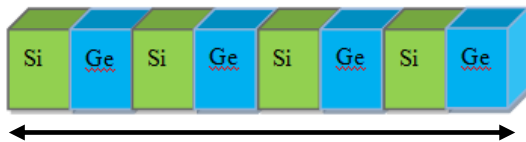

Fig. 1. Periodic structure of 500 layers without defect

II- 1) Mathematical Equations And Analysis Method

We use transfer matrix method for numerical modeling of structure. Since the condition has been studied in TE mode, mathematical equations are as follows:

$$M = \begin{bmatrix} M_{11} M_{12} \\ M_{21} M_{22} \end{bmatrix} = D_0^{-1} \left[\prod_{i=1}^{N} D_l P_l D_l^{-1} \right] D_S \quad (1)$$

$$D_l = \begin{bmatrix} 1 & 1 \\ n_l \cos\theta_l & -n_l \cos\theta_l \end{bmatrix} \quad (2)$$

$$P_l = \begin{bmatrix} e^{-i\phi_l} & 0 \\ 0 & e^{-i\phi_l} \end{bmatrix} \quad (3)$$

$$\phi_l = k_{lx} d \quad (4)$$

$$k_{lx} = n_l \frac{\omega}{c} \cos\theta_l, l = 0,1,2,...,N, S_l \quad (5)$$

$$d_l = x_l - x_{l-1}, l = 0,1,2,3,..., N \quad (6)$$

$$\begin{bmatrix} A_0 \\ B_0 \end{bmatrix} = M \begin{bmatrix} A_S' \\ B_S' \end{bmatrix} \quad (7)$$

In above equations, D is Dynamic matrix and P, propagation matrix. Also θ_l the angle of incident wave, d_l, the distance between two consecutive layers, A_0, B_0, A_S', B_S' coefficients and values of electric field matrix on first and last layer. After calculating dynamic matrix, dynamic inverse matrix and propagation matrix, the amount of conducting band width is studied in boundary and TE mode conditions. Then if we assume that the angle of incident is zero and the distance between two consecutive layers is identical, we can observe and conclude conduct signals (transmission).

$$T = \frac{n_s \cos\theta_s}{n_0 \cos\theta_0} \left| \frac{1}{m_{11}} \right|^2 \quad (8)$$

In above equation, n_0 is refractive index of first layer, n_S, refractive index of last layer, θ_0, the angle of incident wave in first layer and θ_S, the angle of incident wave in last layer.

III. SIMULATION

In this section, we analyze the results of performed simulations and study filter act in three following levels. In simulations the distance between two consecutive layers has been considered equal to $0.5\,\mu m (d_l = 0.5\,\mu m)$.

a) In a condition that there is no defect in considered structure.
b) In a condition that defects are enforced to considered structure.
c) In a condition that graded index method has been used for considered structure.

Explanation: In each above levels, the effect of distance increase between two consecutive layers is studied.

First level: In a periodic structure of 500 layers created by Silicon and Germanium, the characteristic of filter is observed without any defect as Fig. 2 . According to above conditions, we duplicate the distance between two consecutive layers and observe the effect of it on output in Fig. 3 . By comparing two images, we can realize that layers width increase, decrease the amount of filter band width noticeably.

put in 251th layer (as mentioned, discussing structure is a periodic structure with 500 layers that are in symmetrical form, from left to right, with one pair of crystal Silicon and Germanium. We use a pair of air distance (defect) instead of a pair of crystal Si and Ge in 251th layer, the layers after 252, in inverse are from Si and Ge crystals pairs orderly. Layers number in this condition is 501). Then we use five pairs of air layers to analyze the effect of air distance increase. Filter characteristic will be as 5 and 6 Figs.

Fig. 4. Periodic structure of 501 layers with defect

Fig. 2. Filter Characteristic without defect (air distance)

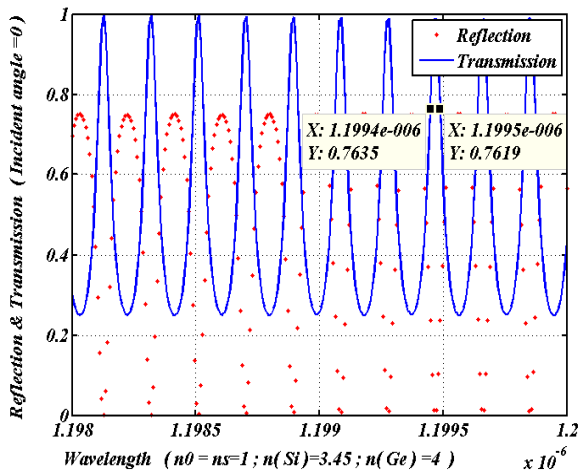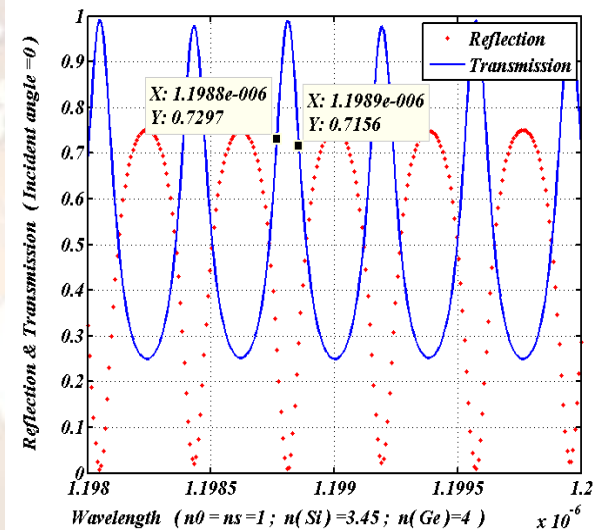Fig. 5. Filter characteristic with a pair of air distance layer

Fig. 3. Filter characteristic without defect (air distance) by duplicating layers width

Second level: Now we study the structure of designed filter band by having defect (air distance). In order to enforce defect in 500 layers structure, according to Fig. 4, a pair of air distance is
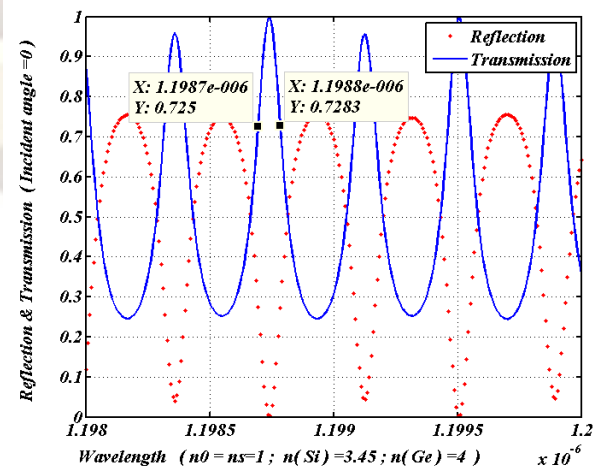

Fig. 6. Filter characteristic with five pairs of air distance layer

In this situation, by comparing 5 and 6 images, we can realize that by increasing the number of air distances, frequency shift (wave length transmission on horizontal axis) is made in filter output. According to above act, if we duplicate the distance between two consecutive layers with defect, filter characteristic will change as Fig. 7.
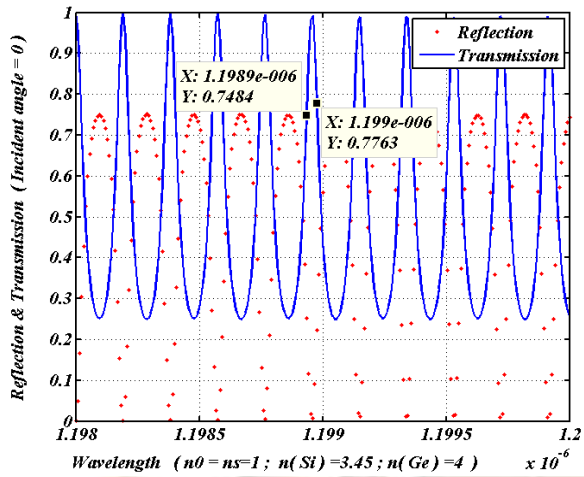

Fig. 7. Filter characteristic with a pair of air distance by duplicating layers width

By comparing Fig. 5 and Fig. 7, we can recognize that in the presence of defect by increasing the layers width, the amount of filter band width decrease noticeably. Also the study of above Images show enforcing defect and increasing layers width, improve filter characteristic noticeably and decrease the width of passing band.

Third level: Now we use graded index method. As you see in Fig. 8, the amount of band width is decreased and it`s put in a acceptable span for conducting signal. In this conditions we can choose passing band. Duplicating the distance between consecutive layers, leads to this output Fig. 9, also we can observe that the width of considered optical filter band has been decreased acceptably.
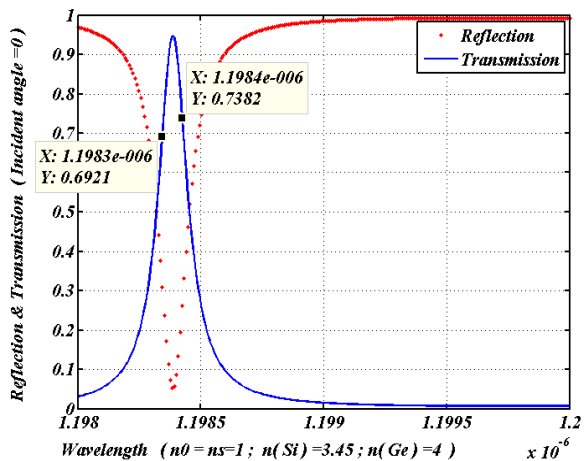

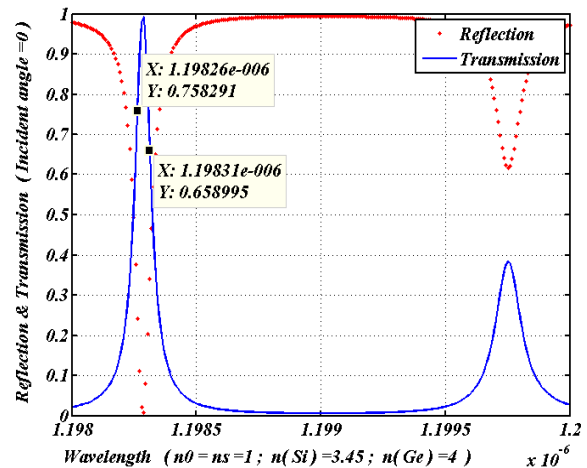Fig. 8. Filter characteristic by graded index method

Fig. 9. Filter characteristic in graded index method by duplicating layers width

Gained results of simulations and above curves are observed in Table 2 . By analyzing the results of table, we can realize that the best band width for considered optical filter is when layers width is duplicated and the amount of it is about 100GHz.

TABLE 2.Wavelength difference between boxing structure

Wavelength transmission (um)	Frequency shift	Smooth refractive index profile (graded index)	Layers width (um)	Air Gap	Parameters / Structure
0.001	No	No	0.5	No	500 layers
0.0001	No	No	1	No	500 layers
0.001	Yes	No	0.5	One pair	501 layers
0.001	Yes	No	0.5	Five pairs	501 layers
0.0001	Yes	No	1	One pair	501 layers
0.0001	Yes	Yes	0.5	One pair	501 layers
0.0001 <	Yes	Yes	1	One pair	501 layers

By studying the following table and above curves, we can conclude that increase in layers width leads to decrease in filter band width. This process is observable by curve analysis of Fig. 10.
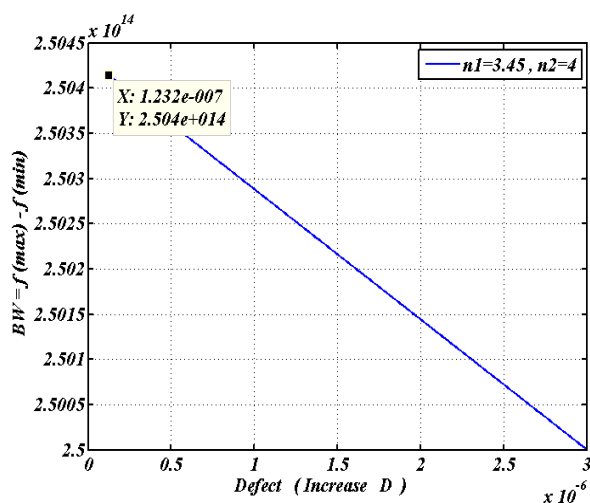

Fig. 10: Decrease of filter band width at layers distance increase ratio

IV. CONCLUSION

In this paper, an adjustable filter has been designed for optical telecommunications systems by one-dimensional photonic structures. Simulation results by TMM method show filtering action limits are about 1 micrometer and passing bands of filter are controlled by defect. Also changing the distance between two consecutive layers, regulates the width of passing band in filter. Results show access to optional wave lengths in passing band of filter is easy and the best passing band width is gained with graded index method.

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