Design And Simulation Of All Optical Multiplexer based On One-Dimensional Photonic Crystal For Optical Communications Systems

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ABSTRACT

In this study a four-channel multiplexer of Dense Wavelength Division Multiplexer (DWDM) has been designed and stimulated by one-dimensional photonic crystal structure to be used in optical telecommunication purposes of C band. It has been formed of both Germanium and Silicone crystals based on grading method of refraction factor profile (Apodization). In this process by means of Transfer Matrix Method (TMM), light refraction theorem and defect exertion, the effect of radiated optical signal angle to studied structure and optical multiplexer has been made by too narrow channels.

Keywords- C band , Multiplexer , Photonic crystals , Transfer Matrix Method (TMM)

I. INTRODUCTION

Since, access to high speed and capacity in transmitting and receiving data is under the attention of researchers, optical telecommunication systems has been considered based on laser and optical fiber. Therefore in this kind of structure, by making all devices optical, we can remove the problem of low speed in systems that use electric signal [1], [2]. These all optical networks can be replaced by present optical fiber systems that are optoelectronic segments. In this condition, we have to use the technology of all optical networks [3], [4]. So "photonic crystals" usage matter is presented, these crystals because of having unique linear and nonlinear features are used in optical communications [5]. This naming reason is related to their periodic structure and function in light. In fact, they are periodic items of dielectric materials that optical waves (electromagnetic) can`t pass through them in special frequency spans, this area is called photonic gap band [6], [7]. So by breaking the alternative period of photonic crystal, we can engineer light diffusion into it. For example, we can make some changes in band structure of photonic crystal by defect to make optical waveguide with less loss [8] , optical switches [9] , filters , resonators , multiplexers and optical demultiplexers for wavelength division multiplexer (WDM) networks [10]-[16].

Since multiplexers and demultiplexers are from required basic blocks, for combing and separating a great number of channels in WDM networks, we studied four channel optical multiplexer and tried to decrease the channel width of data transmission as far as possible. So by making all equipment optical, we can increase the speed and capacity of data transmission in communication industry. In this section, at first we will discuss multiplexing method and then will study suggested structure.

A. DWDM and CWDM methods contrasts

The method of wavelength division multiplexer (WDM) is used as main method in data transfer of optical systems [19]. In this method, several optical signals are combined to each other and then are amplified and transmitted as a collection. It leads to increase in data transfer capacity. So one of the advantages of this method is the ability in transmitting a lot of optical channels in different formats by one fiber and each channel can transfer 2.5 Gb/s or more data [20], [21], diagram block of this process has been showed in figure 1. Amplifiers that amplify optical signals without converting to electrical signals have made WDM too valuable and useful.
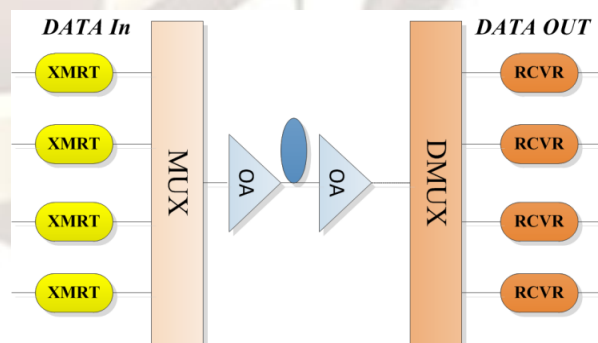

Fig.1 Structure of wavelength division multiplexer
- Multi_channel WDM operation
- Date-rate and modulation-format transparent
- One optical amplifier (per fiber) supports multiple channels
- 80-140 km amplifier spacing
- Distortion and noise accumulate (OA)

• Graceful growth

WDM method has two kinds:

• Dense wavelength division multiplexed (DWDM)
• Coarse wavelength division multiplexed (CWDM)

The basic difference of these two methods is in distance between channels. In DWDM the distance among channels is 0.4 nm [23] and each channel provides 10 Gb/s bandwidth for users. This method is applied based on table 1 in L and C bands limits and 32 to 160 channels are created that with this number of channels, we can get 160 Gb/s – 1600 Gb/s bandwidth, in contrast, in CWDM, the distance among channels is 20 nm and so 18 wavelength (with 13 nm channel width) are used in 1260 nm to 1625 nm limits of L, C, S, E and O bands [24], [25] and it will provide up to 40 Gb/s bandwidth on one fiber, lonely [26],[27].

Table 1. Characteristics of Communication Bands In Wavelength Limits

Band name	Wavelength range by Nano-meter
O-Band	1260– 1360
E-Band	1360 – 1450
S-Band	1450 – 1530
C-Band	1530 – 1565
L-Band	1565 – 1625

B. The advantages of optical fiber multiplexers design

Nowadays, by increase in demand for more channel width in optical networks, the number of optical channels should be increased, so for having maximum use of fiber capacity in WDM method, we should decrease the distance among channels [22], so this design is according to DWDM and it has tried to decrease the amount of channel width to less than 1 nanometer.

II. ANALYSIS METHOD

In this paper, we study and stimulate a DWDM network as a 4 to 1 multiplexer in C band subset by one-dimensional photonic crystals. Parameters such as layers refraction factor, the distance among layers, layers number and their arrangement are all effective on the type of structure behavior [6], [7].

For studying results, defect exertion technic was used to periodic network. To get frequency limits and considered bandwidth, we engineer photonic gap band by defect and the analysis of transfer matrix method (TMM) analyze the structure and study the frequency respond.

A.TMM

In order to study and calculate passing , reflecting and refracting components of light into a one or multilayer structure, we use Maxwell`s equations under physics frontier conditions for E, D, B and H fields [28], [29]. For getting magnetic and electrical field domain in multilayer isotopic structures, matrix method is too suitable. Because when the number of layers is much, the number of equations that should be solved will be high. It makes equations analysis too complicated. Therefore TMM will be too useful. Also we can use this method in conditions that the big part of structure is periodic [27]. So this method is applied to photonic crystals and it has been designed in a way that is suitable for one-dimensional photonic crystal structures but because of equations difficulty in frontier conditions, TMM has no use in two and three- dimensional photonic crystals [28], [29].

III. INTRODUCING STRUCTUER

In this paper, we present two structures as figure 2 and 3.
1)   500 layer structure, this structure is symmetrical from left to right, from first layer up to 250th layer, it has one pair of Germanium and Silicone crystals with the refraction factors of $n_{Ge} = 4$ and $n_{Si} = 3.45$, from 251th layer up to 500th layer, layers are reversed with one pair of Germanium and Silicon crystals.
2)   501 layer structure, this structure looks like previous structure with these differences:
First: After 250th layer , it has one pair of air distance
($n_{Air} = 1$) as defect.

Second: For having better quality and optimal control on output bandwidth, grading method of refraction factor profile has been used.
In second structure, after 170th layer, we exert grading method of refraction factor profile, it means in 80 layers or 160 levels with $step = -0.01875$, we lower refraction factor from $n_{Ge} = 4$ to $n_{Air} = 1$ and then we do the reverse form of upper actions with $step = +0.01875$ and raise the refraction factor from $n_{Air} = 1$ to $n_{Ge} = 4$.

In fact refraction factors of 161 middle layers are increased and decreased based on this trend, they totally make a 501 layer structure with first and last layers. Note that in this state, 251th layer is air which is defect.
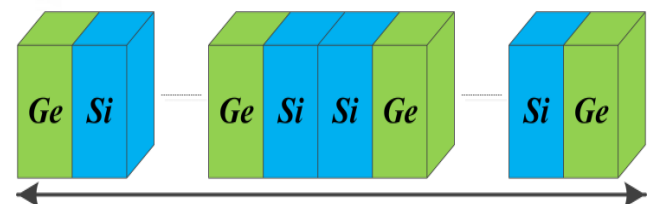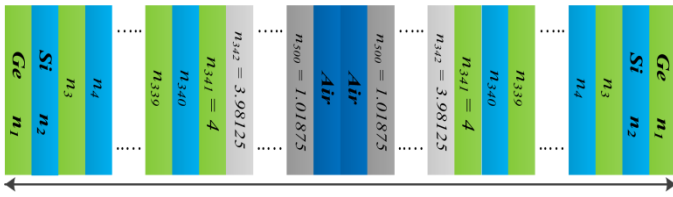

Fig. 2 Periodic structure of 500 layers without defect

Fig. 3 Periodic structure of 501 layers with defect (one layer of air)

IV. MATHEMATICAL MODEL

For numeral modeling of structure, we use TMM. Since the conditions have been studied in TE mode, according to Fig. 5, mathematical equations are as follows:
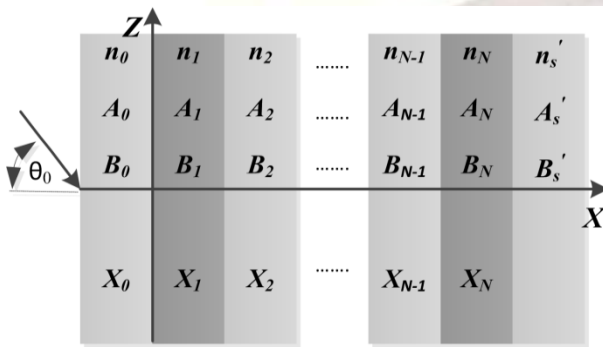

Fig. 4 A multilayer dielectric medium

$$TE = \begin{cases} \dfrac{\partial H_Z}{\partial y} = \dfrac{\partial E_X}{\partial t} + \partial E_X \\ -\dfrac{\partial H_Z}{\partial x} = \varepsilon \dfrac{\partial E_y}{\partial t} + \partial E_y \\ \dfrac{\partial E_y}{\partial x} - \dfrac{\partial E_X}{\partial y} = -\mu \dfrac{\partial H_Z}{\partial x} - \sigma_m H_Z \end{cases} \quad (1)$$

$$E = E(x)e^{i(\omega t - \beta t)} \quad (2)$$

In Equation 2, β is z component of wave vector and ω, angle frequency. In this equation, it`s supposed that electromagnetic wave is diffused in XZ surface. In equation 2, electrical field E(X), has left and right components that we write as following form:

$$E(x) = R\, e^{ik_x x} + L e^{-ik_x x} \equiv A(x) + B(x) \quad (3)$$

In Equation 3, $\pm k_x$ is x component of wave vector, R and L are constant in every compatible layer. We show the wave domain of right side with A(x) and the wave domain of left side with B(x).

$$E(x) = \begin{cases} A_0 e^{-ik_{0x}(x-x_0)} + B_0 e^{-ik_{0x}(x-x_0)} & x < x_0 \\ A_l e^{-ik_{lx}(x-x_l)} + B_l e^{-ik_{lx}(x-x_l)} & x_{l-1} < x < x_l \\ A_s' e^{-ik_{sx}(x-x_N)} + B_s' e^{-ik_{sx}(x-x_N)} & x_N < x \end{cases} \quad (4)$$

$$M = \begin{bmatrix} M_{11} M_{12} \\ M_{21} M_{22} \end{bmatrix} = D_0^{-1} \left[\prod_{i=1}^{N} D_l P_l D_l^{-1} \right] D_S \quad (5)$$

$$D_l = \begin{bmatrix} 1 & 1 \\ n_l \cos\theta_l & -n_l \cos\theta_l \end{bmatrix} \quad (6)$$

$$P_l = \begin{bmatrix} e^{-i\phi_l} & 0 \\ 0 & e^{-i\phi_l} \end{bmatrix} \quad (7)$$

$$\phi_l = k_{lx} d \quad (8)$$

$$k_{lx} = n_l \frac{\omega}{c}\cos\theta_l, l = 0,1,2,...,N, S_l \quad (9)$$

$$d_l = x_l - x_{l-1}, l = 0,1,2,3,..., N \quad (10)$$

$$\begin{bmatrix} A_0 \\ B_0 \end{bmatrix} = M \begin{bmatrix} A_S' \\ B_S' \end{bmatrix} \quad (11)$$

In above equations, D is dynamic matrix and P, diffusion matrix. Also θ_t is the angle of landing wave, d_l, the distance between two continuous layers and $A_0, B_0, \acute{A}_s, \acute{B}_s$, the factors and amounts of electrical field matrix in first and last layer. By calculating dynamic matrix, the reverse of dynamic matrix and diffusion matrix, we can study the amounts of transmission bandwidth in frontier condition and TE mode. Then we suppose the amount of land wave angle (θ_t) is equal to zero and the distance between two continuous layers (d_l) is identical, now we can observe signal transmission diagrams.

Transmittance T is given by:

$$T = \frac{n_s \cos\theta_s}{n_0 \cos\theta_0} \left| \frac{1}{m_{11}} \right|^2 \quad (12)$$

In above equation, n_0 is refraction factor of first layer, n_s , refraction factor of last layer, θ_0, the angle of landing wave in first layer and θ_s , the angle of landing wave in last layer.

V. SIMULATION

In this structure, layers width is proportionate and equal to 125 nm. Input angles have been considered in 0 to 90° limits. Since our purpose is to design a four channel multiplexer with maximum 1nm channel width, we should choose radiation angle in a way that not only the channel width is less than 1 nm but also channels do not have any interference. According to this matter and software analysis, we calculated the angles of 6, 16, 28 and 72° and we can observe multiplexer output for mentioned angles in 6, 7, 8 and 9 figures. Also we study the effect of air layers number and layers width decrease on mentioned angles output.

Therefore stimulations will happen in four states:

A. Layer width is 125 nm and it`s without air layer (structure has 500 layers.)

B. Layer width is 125 nm and it has one air layer and grading method of refraction factor profile in 160 middle layers (structure has 501 layers.)

C. Layer width is 125 nm and it has three air layers and grading method of refraction factor profile in 160 middle layers (structure has 501 layers.)

D. Layer width is 115 nm and it has one air layer and grading method of refraction factor profile in 160 middle layers (structure has 501 layers.)

So at first output is shown lonely for each angle and then we analyze caused changes of above states on output. Since C band limit is considered in analysis conditions, we according to Fig. 5, output has been observed and studied in wavelength limits of 1530 nm to 1565 nm.
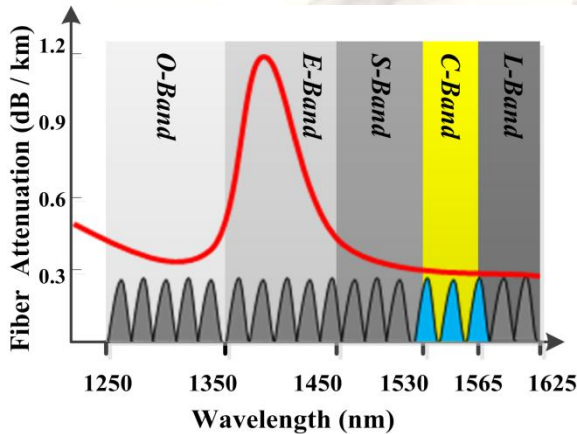
Fig. 5 Communication wavelength limits and bandwidth selection of stimulated multiplexer in C band limit
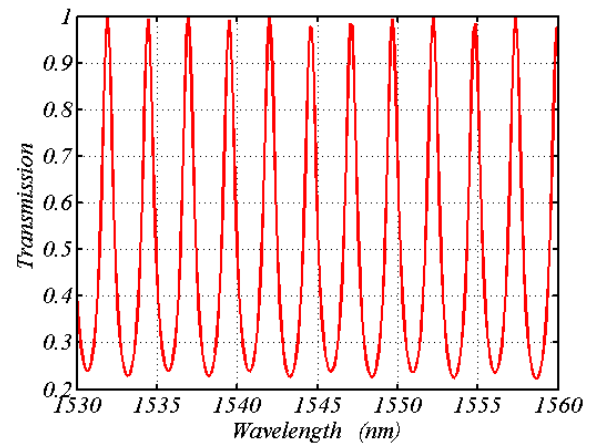
First state: layers width is 125 nm and it`s without air layer (structure has 500 layers) :
In this state outputs of mentioned angles (6, 16, 28 and 72) are as following figures.
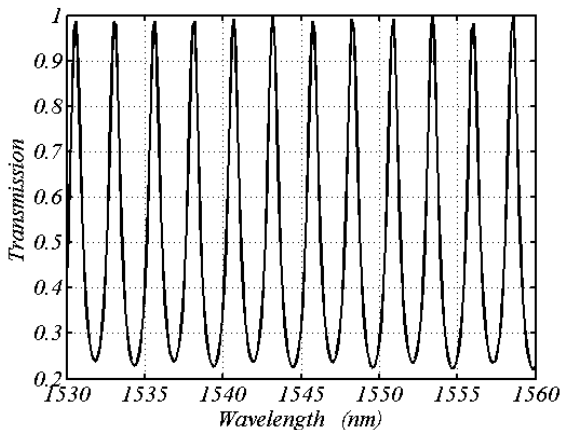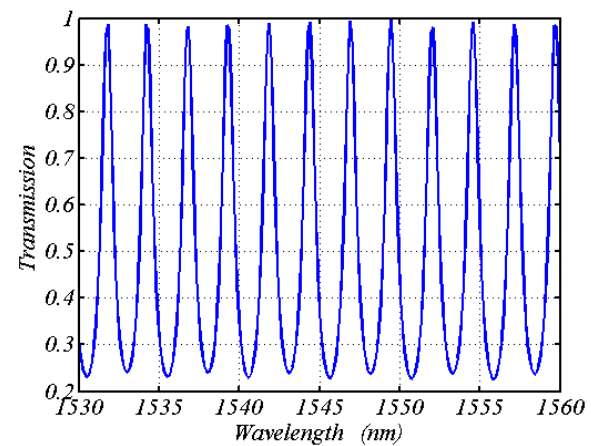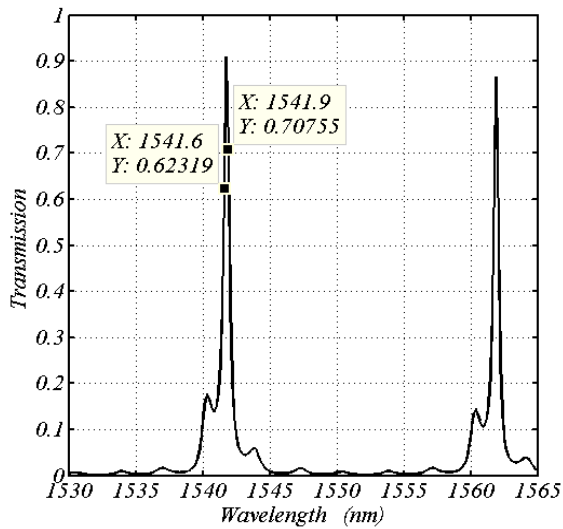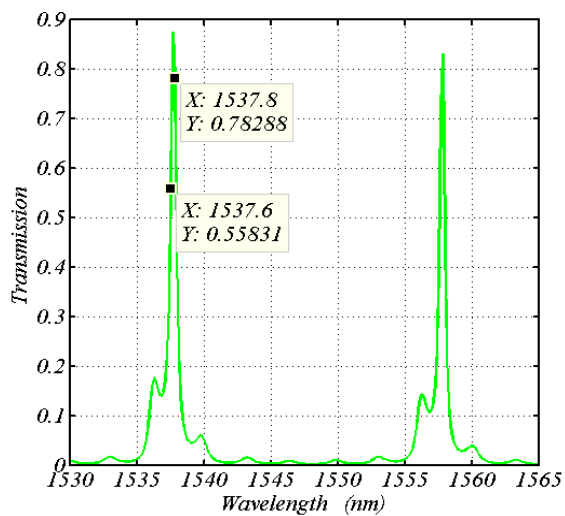

(a)
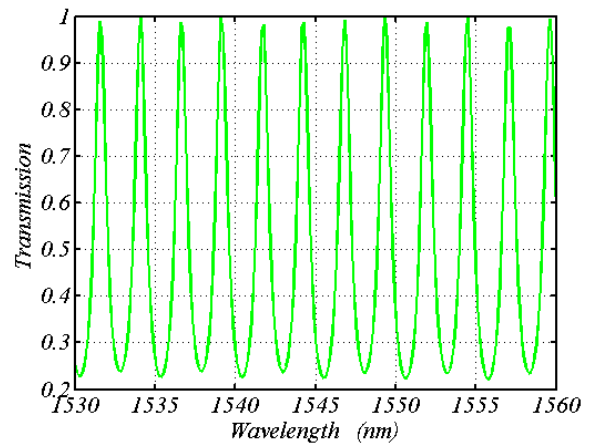
(b)

(c)

(d)

Fig. 6. Output for input radiated a) angle of $6°$, b) angle of $16°$, c) angle of $28°$, d) angle of $72°$

By comparing above figures, we can conclude that there is no control on output data of considered C band limit and we can not get special channel for this multiplexer structure and totally all four channels will have interference simultaneously. Second state: Layers width is 125 nm and it has one air layer and grading method of refraction factor profile in 160 middle layers (structure has 501 layers) :
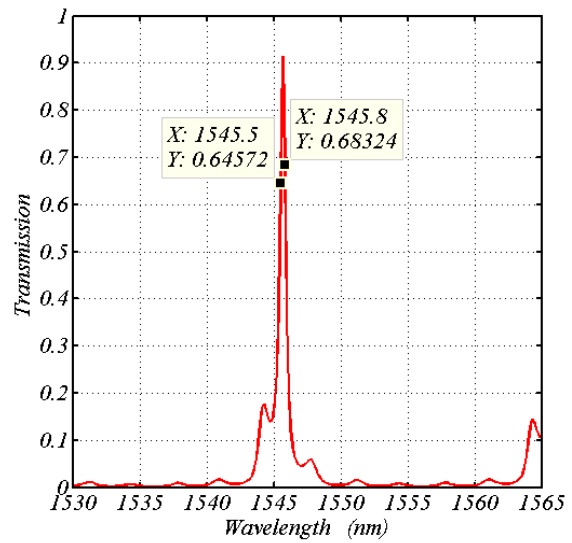
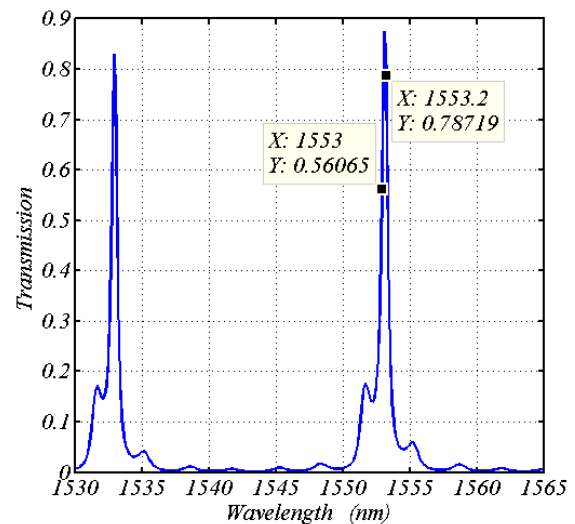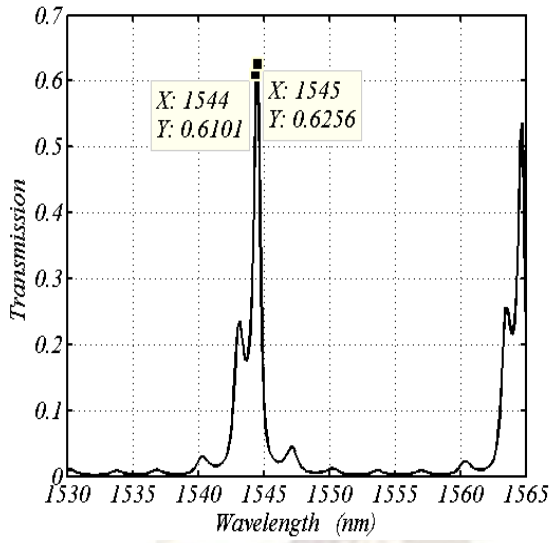In this state, outputs of mentioned angles are as following figures.

(a)

(b)

(c)

(d)

Fig. 7. Output for input radiated a) angle of $6°$, b) angle of $16°$, c) angle of $28°$, d) angle of $72°$

According to above figures,we can conclude that some wavelengths have been omitted by using of defect and grading method of refraction factor profile, channel width has been gotten to less than 1 nm and four isolated channels have been made without interference.
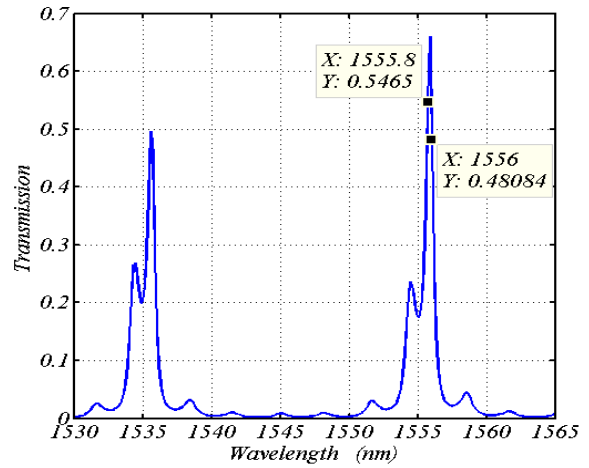Third state: Layers width is 125 nm and it has three air layers and grading method of refraction factor profile in 160 middle layers (structure has 501 layers) :

In this level , we study the effect of air layers

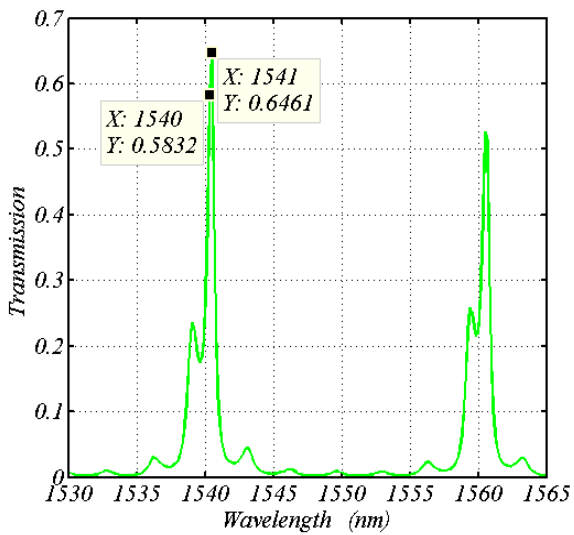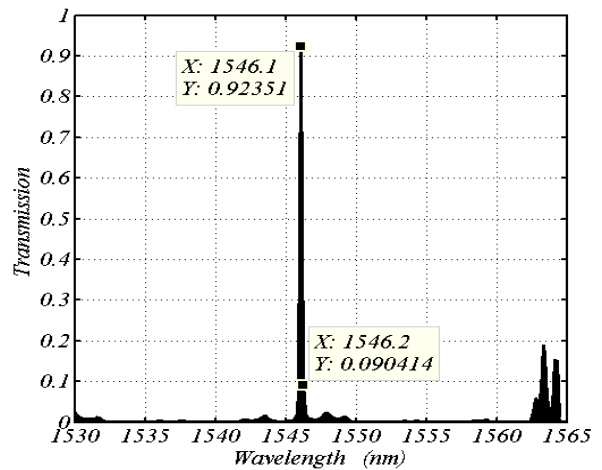number on multiplexer   output. Outputs   are as following figures.

(a)

(b)

(c)

(d)

Fig. 8. Output for input radiated a) angle of 6°, b) angle of 16°, c) angle of 28°, d) angle of 72°
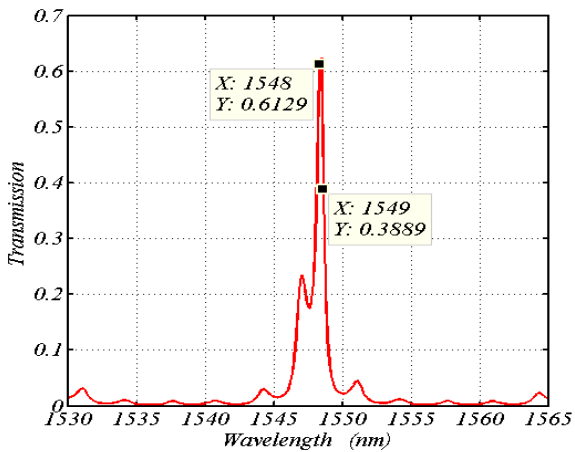
Now, the effect of decrease in layers width is studied on channels. Mentioned angles output are as following figures.
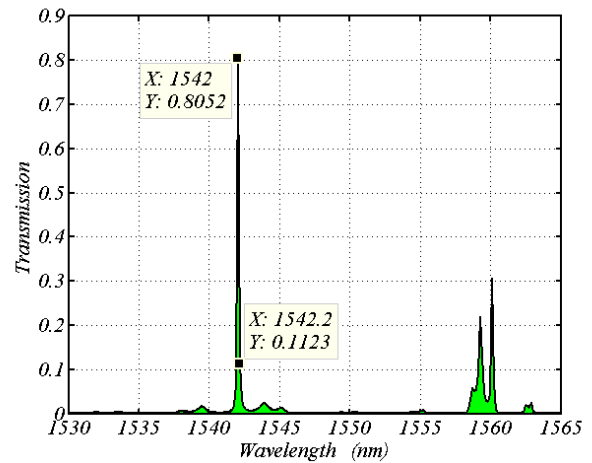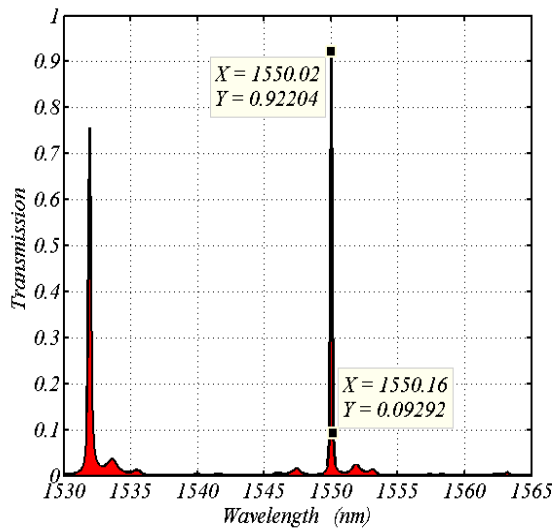

(a)

(b)

(c)
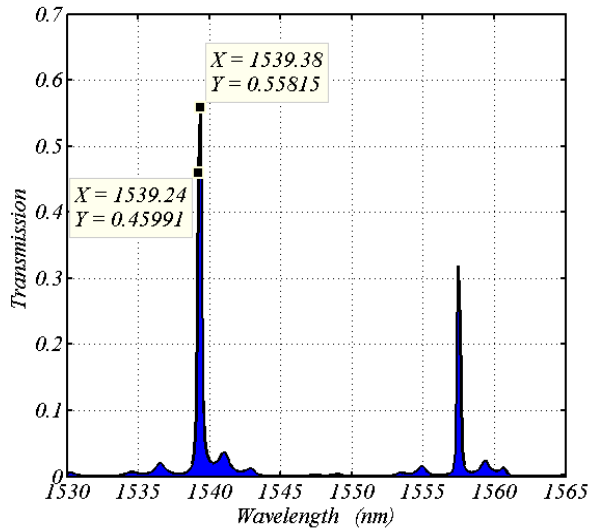
(d)

Fig. 9. Output for input radiated a) angle of 6° , b) angle of 16° , c) angle of 28° , d) angle of 72°

By analyzing above figures , we can conclude that decrease in layers width leads to frequency shift and it decreases the amount of transmission partly. So we can`t say decrease in layers width improves output.

To understand better, we can observe multiplexer output simultaneously in all studied angles in each 10.a, 10.b and 10.c figures.
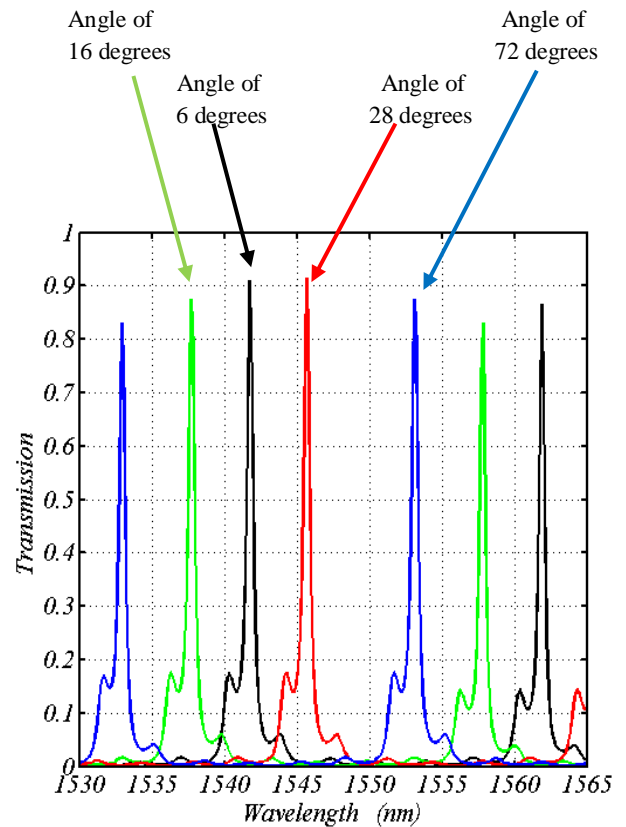
(a)

Fig. 10. Multiplexer output by apodization method, one air layer and 125 nm layers width
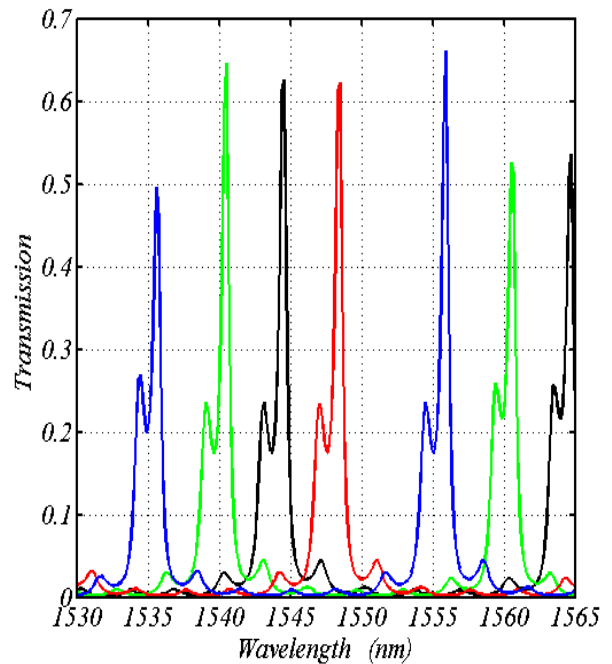
(b)

(c)

Fig. 10. Multiplexer output by apodization method , a) , one air layer and 125 nm layers width , b) three air layer and 125 nm layers width , c) without air layer and 115 nm layers width

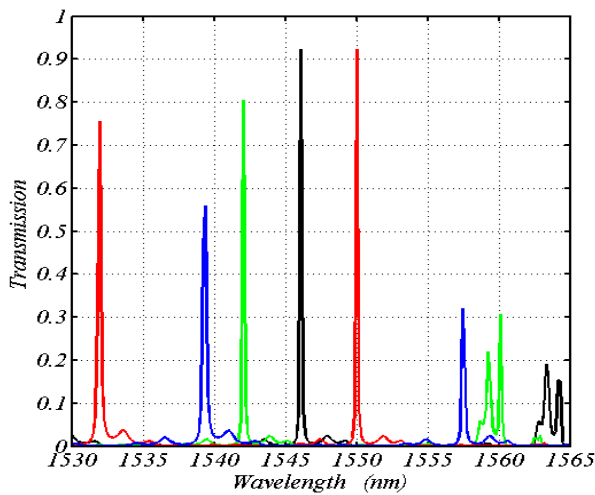By studying all figures, we get that in all four states, channel width is less than 1 nm but just second state is suitable to use, because in this state, channels have no interference and the amount of transmission is in acceptable level (reflection amount is least). Since increase in defect and decrease in layers width lead to frequency shift and transmission amount is decreased considerably, we will have reflection and it means some data will be lost.

Obtained results of stimulations are provided briefly in table 2.

Table 2. Study of 4 to 1 multiplexer frequency limit based on the effects of air distance , shift and frequency interference

Parameters / Structuer	Air Gap	Layers width (nm)	Smooth refractive index profile (graded index)	Frequency shift	Frequency Interference	Wavelength transmission (nm)
500 layers	No pair	125	NO	No	Yes	$\cong 1$
501 layers	One pair	125	Yes	No	No	≤ 1
501 layers	Three pair	125	Yes	Yes	No	≤ 1
501 layers	One pair	115	Yes	Yes	Yes	≤ 1

VI. CONCLUSION

In this paper, by using of one-dimensional photonic structures, we designed a filter and multiplexer for optical telecommunication systems in C band limits. This multiplexer lets signals that are radiated under special angle, pass.

Stimulation results by TMM show by using of defect and suitable grading method of refraction factor profile, channel width is decreased to less than 1 nm and we can have channels that are without interference. In fact we can control channel and passing bands width with defect and apodization. Stimulation results show changing in the number of air layers and layers width not only decrease transmission considerably, but it also leads to frequency shift that may cause interference in output.

So we can`t get a multiplexer with no interference in telecommunication C band. Therefore the best output is gained with the width of 125 nm by means of one air layer and grading method of refraction factor profile.

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