

# All optical multi reflection structure based on one dimensional photonic crystals for WDM communication systems

FARHAD MEHDIZADEH, HAMED ALIPOUR-BANAEI<sup>a,\*</sup>, ZIADDIN DAIE-KUZEKANANI<sup>b</sup>

*Electrical Department, Faculty of Engineering, Ahar Branch, Islamic Azad University, Ahar, Iran*

*<sup>a</sup>Electrical Department, Faculty of Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran*

*<sup>b</sup>Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran*

In this paper we proposed a narrow band all optical multi reflectionband filter based on one dimensional photonic crystal structures. The minimum quality factor of our filter is 7757 and the band gap width of our structure was less than 0.2 nm. We also tested our structure under different incident angles. We also observe that the number of the bi layers has no effect on the band structure of the filter. We used Transfer Matrix Method (TMM) to do our calculations.

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## 1. Introduction

Since 1987, in which the Photonic Crystals (PhCs) have been proposed [1-2] they have been one of the most interesting fields for researchers to work on it. As far as we know photonic crystals are periodic arrays of dielectric layers with alternating refractive indices. The period of these arrays is called lattice constant. According to their structure and the periodicity of the refractive index distribution they are divided into 3 categories: one-dimensional, two-dimensional and three-dimensional photonic crystals (1D PhC, 2D PhC and 3D PhC). One of the most important characteristics of these artificial structures is their Photonic Band Gap (PBG). Photonic band gap is a special region in the band structure of photonic crystals in which no optical wave is allowed to propagate through them. That is, any optical ray striking to these structures, if its wavelength be in the band gap range of the photonic crystal, the ray will be reflected completely and it won't be able to penetrate into the structure [3-4]. Optical circulators [5], optical switches [6], power splitters [7], optical demultiplexers [8-9] and optical filters [10] are some reported examples of photonic crystal based devices.

The primary role of optical filters for optical communication networks has been completely determined by researchers in the last few decades. On the other hand, optical filters are key devices for optical communication systems [11]. The first step towards optical networking was the advent of Wavelength Division Multiplexing (WDM) and Dense Wavelength Division Multiplexing (DWDM) [12-14]. The main attraction of WDM was the ability to multiply the capacity of a single fiber. By this technology a fiber could carry 4, 8, 16, 32, 40 or more

optical channels at different central wavelengths. An optical filter can pick off the desired optical channel [15]. In other words, optical filters are used to separate one optical channel from the combined signal without the use of electronics. One of the main applications of optical filters is for demultiplexing very closely spaced channels [16-18]. Of course sometimes we need to stop some channels so we need stop band channels.

One-dimensional photonic crystal filters are very popular among the researchers. Defect mode properties [19], light transmission characteristics [20] and photonic band gap controlling [21] in one-dimensional photonic crystals have been investigated. There have been many kind of one-dimensional photonic crystal filters. For example a 1D Si/SiO<sub>2</sub> photonic crystal filter for thermo photovoltaic applications has been proposed [22] in which large oscillations around 1.45-1.75  $\mu\text{m}$  in the pass band of this PhC filter would reduce the above band gap power transmitted to cells, leading to discounts of system efficiency and power density. Another example of recent works on 1D photonic crystal is a narrow pass band and narrow transmission angle filter [23]. This structure was composed of two parts: the first part was a 1D PhC with positive refractive index defect layer and the second part was a 1D PhC with negative refractive index defect layer. So it was capable of filtering the incident angle and only the waves which are normal to the structure at the specified frequency are allowed to transmit through the filter.

But in this work we aim to design a narrow band multi-channel filter with high Q-factor. Since the Transfer Matrix Method [24] is the simplest and the most straight forward tool for analyzing 1D PhCs we employ it to do our simulations and calculations.

## 2. Mathematical theory

Our 1D PhC based filter is shown in Fig. 1. It consists of 20 periodic dielectric layers with alternating refractive indices. We used Transfer Matrix Method (TMM) to investigate the propagation of electromagnetic waves in our structure. First we briefly introduce the TMM method:

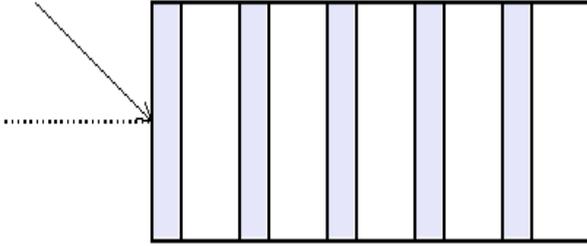


Fig. 1. The schematic of our structure with 20 layers.

In the proposed structure (Fig. 1)  $n_1$  and  $n_2$  are the refractive index of first and second layers, respectively in each period and the thicknesses of the first and second layers are  $h_1$  and  $h_2$  respectively. In TMM we have to matrices for each layer.

A dynamical matrix given by:

$$D_m = \begin{cases} \begin{bmatrix} 1 & 1 \\ n_m \cos \theta_m & -n_m \cos \theta_m \end{bmatrix} \text{for TE wave} \\ \begin{bmatrix} \cos \theta_m & -\cos \theta_m \\ n_m & -n_m \end{bmatrix} \text{for TM wave} \end{cases} \quad m = 1, 2 \quad (1)$$

And a propagation matrix given by:

$$P_m = \begin{bmatrix} \exp(ik_m h_m) & 0 \\ 0 & \exp(-ik_m h_m) \end{bmatrix} \quad m = 1, 2, \quad (2)$$

Where  $k_m = \omega n_m \cos \theta_m / c$  is the wave vector,  $\omega$  is the angular frequency, and  $\theta_m$  is the ray angle in each layer. For each period (bilayer) the transfer matrix is equal to:

$$M_p = D_1 P_1 D_1^{-1} D_2 P_2 D_2^{-1} \quad (3)$$

And the transfer matrix of total structure with N period is:

$$M = \begin{bmatrix} M_{11} & M_{21} \\ M_{21} & M_{22} \end{bmatrix} = D_0^{-1} M_p^N D_0 \quad (4)$$

Where  $D_0$  is the dynamical matrix of air given by:

$$D_0 = \begin{cases} \begin{bmatrix} 1 & 1 \\ n_0 \cos \theta_0 & -n_0 \cos \theta_0 \end{bmatrix} \text{for TE wave} \\ \begin{bmatrix} \cos \theta_0 & -\cos \theta_0 \\ n_0 & -n_0 \end{bmatrix} \text{for TM wave} \end{cases} \quad (5)$$

Where  $n_0$  and  $\theta_0$  are the refractive index of air and the angle of incident ray of light. We used  $D_0$  and  $D_0^{-1}$ , because the proposed structure is surrounded by air. The transmission coefficient,  $t$  and the reflection coefficient  $r$  are:

$$r = \frac{M_{21}}{M_{11}} \quad (6)$$

And

$$t = \frac{1}{M_{11}} \quad (7)$$

Now we have the transmittance,  $T$  and reflectance,  $R$  as follow:

$$T = |t|^2 \quad (8)$$

And

$$R = |r|^2 \quad (9)$$

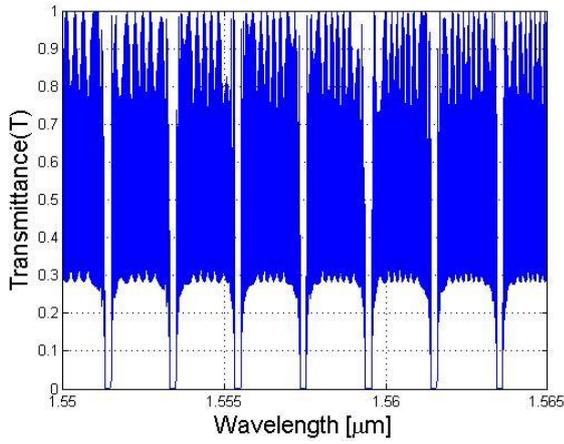
## 3. Calculation and results

In order to find the photonic band structure and photonic band gap of our structure we should calculate the (1). We did this job with MATLAB Code for TMM. We did the calculations both for TE mode and TM mode. For normal incident ( $\theta=0$ ) the transmission spectrum for TE/TM modes are the same. We employed GaP for the first layer and GaSb for the second layer, their refractive indices in our desirable wavelength range (1.5-1.6  $\mu\text{m}$ ) are 3 and 4, respectively. As far as we know most 1D photonic crystal structures follow the Bragg rule that says [24]  $n_1 h_1 + n_2 h_2 = \lambda_0 / 2$  and  $n_1 h_1 = n_2 h_2 = \lambda_0 / 4$ .

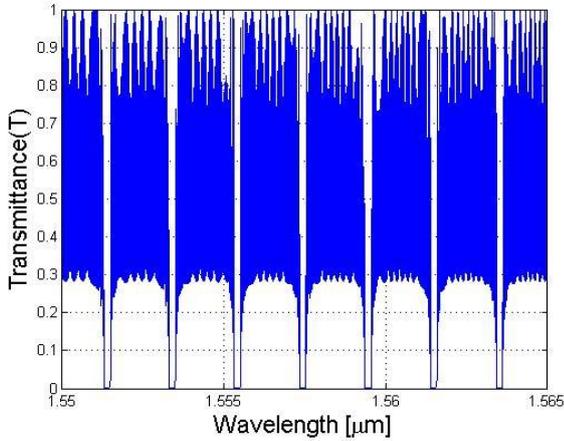
By these conditions we will have one large photonic band gap, but in order to have multiple narrow band reflection channels in our desirable wavelength range (1.5-1.6  $\mu\text{m}$ ) we should not follow the Bragg rule. Our simulations showed that if we choose  $h_1$  and  $h_2$  to be 200 and 150  $\mu\text{m}$ , respectively in our desirable wavelength range (1.5-1.6  $\mu\text{m}$ ) we will have multiple narrow band reflection channels. As you can see in Fig. 2 we have 7 band gaps in less than 15 nm wavelength range. The Q-factor of our filter ( $Q = \lambda_0 / \Delta \lambda$ ) both in TE/TM modes is near 7750 and the band width of each channel is less than 0.2 nm. The exact Q-factor for all channels is summarized in Table 1.

Table 1. The  $Q$  factor of the channels.

Channel	$\lambda_0$ (nm)	$\Delta\lambda$ (nm)	$Q$
1	1551.4	0.2	7757
2	1553.4	0.2	7767
3	1555.4	0.2	7777
4	1557.5	0.2	7787.5
5	1559.4	0.2	7797
6	1561.5	0.2	7807.5
7	1563.5	0.2	7817.5



(a)



(b)

Fig. 2. Band structure of our 1D PhC filter in (a) TE and (b) TM mode.

We tested our structure under in both TE/TM modes under different incident angles and the results are depicted in Fig. 3 and Fig. 4. Fig. 3 shows the effect of incident angle on the band structure of our filter in TE mode. As we can see from Fig. 3 when the incident angle is normal ( $\theta=0$ ) to the filter we have 7 band gaps in the proposed wavelength range but for  $\theta=\pi/6$ ,  $\pi/4$  and  $\pi/3$  we have 14 band gaps. We have to mention that because of simplicity we only show this ranges in the pictures however it continues up to 1.6  $\mu\text{m}$  in the same way.

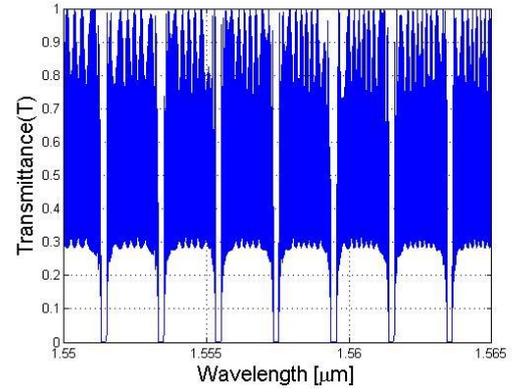
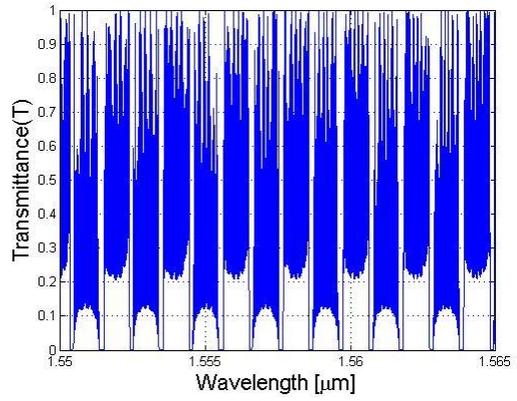
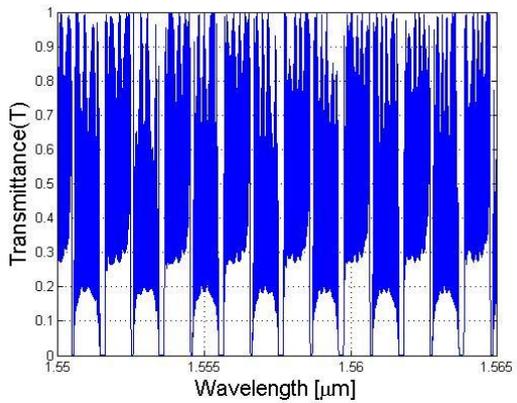
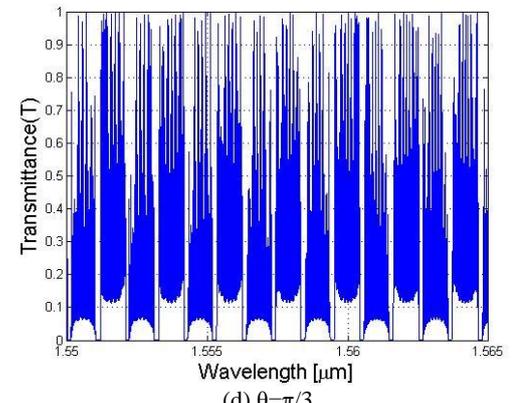
(a)  $\theta=0$ (b)  $\theta=\pi/6$ (c)  $\theta=\pi/4$ (d)  $\theta=\pi/3$ 

Fig. 3. Effect of incident angle on the band structure in TE mode.

Fig. 4 shows the effect of incident angle on the band structure of our filter in TE mode. As we can see from Fig. 4 when the incident angle is normal ( $\theta=0$ ) to the filter and for  $\theta=\pi/3$  we have 7 band gaps in the proposed wavelength

range but for  $\theta=\pi/6$  and  $\pi/4$  we have 14 band gaps. We have to mention that because of simplicity we only show these ranges in the pictures however it continues up to  $1.6 \mu\text{m}$  in the same way.

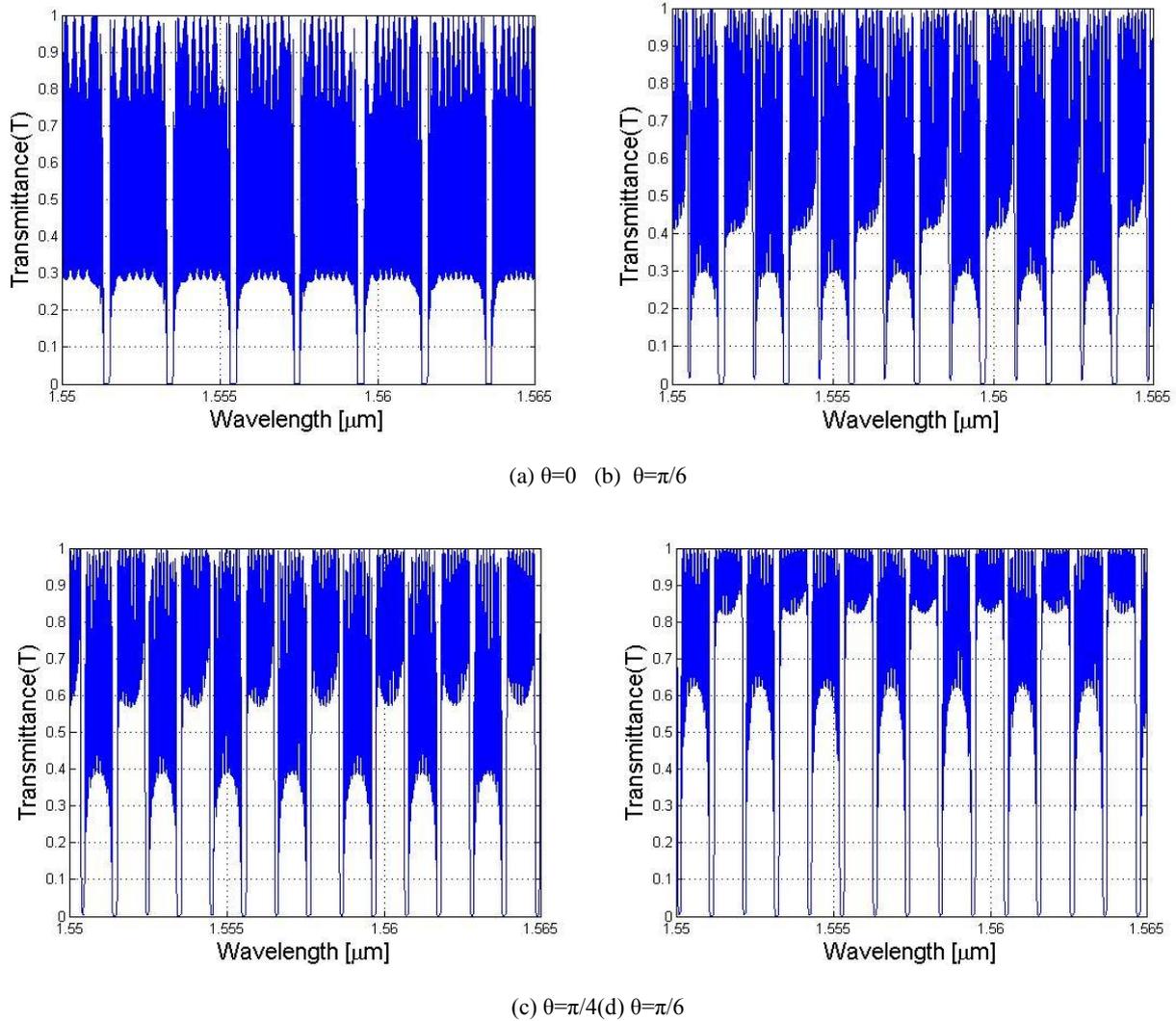


Fig. 4 Effect of incident angle on the band structure in TM mode.

We also tested different number of bi-layers (one period of layers ( $N$ )) in our filter and as Fig. 5 shows the number of the periods has no significant effect on the band structure of our 1D photonic crystal filter.

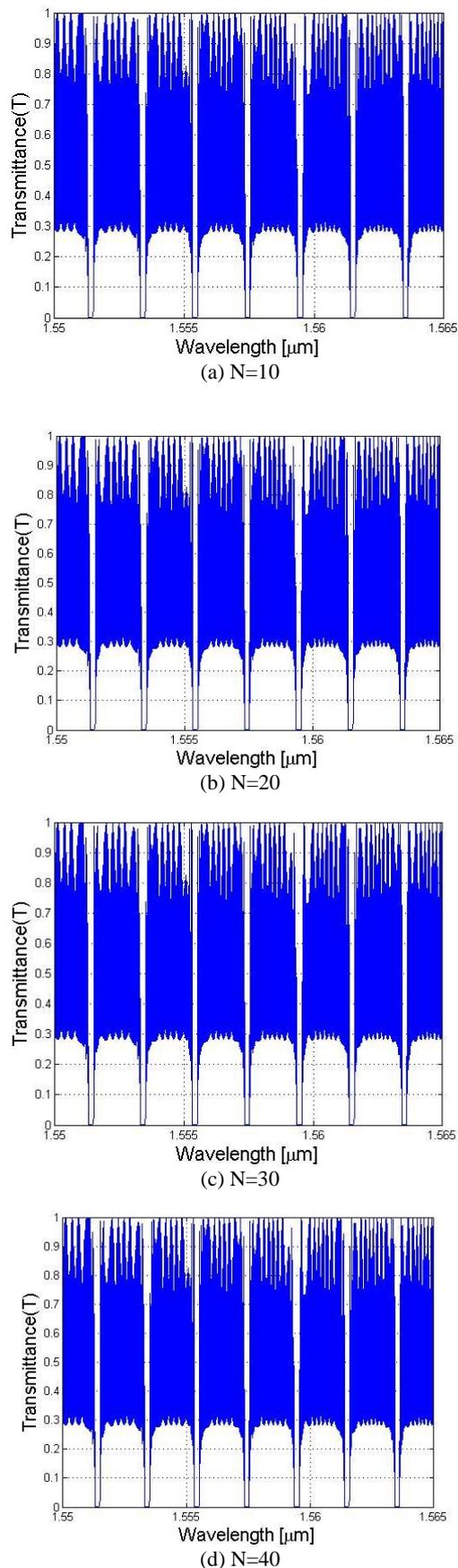


Fig. 5. Band structure of the 1-D photonic crystal filter for different number of bilayers.

#### 4. Conclusion

In this paper we proposed a narrow band multichannel reflection based on 1D photonic crystal. We showed that by increasing the thicknesses of the layers beyond the Bragg rule we can achieve a narrow band multichannel reflection filter with very small band width and high quality factor such that the band gap width of our structure is less than 0.2 nm and the quality factor is around 7757. We also tested our structure under different incident angles. In TE mode when the  $\theta=0$  we have 7 band gaps in the proposed wavelength range but for  $\theta=\pi/6, \pi/4$  and  $\pi/3$  we have 14 band gaps and in TM mode when  $\theta=0$  and  $\pi/3$  we have 7 band gaps in the proposed wavelength range but for  $\theta=\pi/6$  and  $\pi/4$  we have 14 band gaps. We also observe that the number of the bi layers has no effect on the band structure of the filter.

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\*Corresponding author: alipour@iaut.ac.ir