Progress In Electromagnetics Research Letters, Vol. 71, 61–67, 2017

Modeling of Multichannel Filter Using Defective Nano Photonic Crystal with Thue-Morse Structure

Hadis Azarshab* and Abdolrasoul Gharaati

Abstract—In this work, we study a multichannel filter by using one-dimensional photonic crystal (1DPC) based on Thue-Morse sequence (TMS). We use a dielectric defect layer between binary sequence cells with a TMS structure. First, we show transmission in terms of wavelength for the structure without defect layers. Then, we plot transmission in terms of wavelength for a different number of defect layer periods (N) in normal incidence. The analysis shows that there are two photonic bang gaps (PBG) in visible and infrared regions and two defect modes in each one for $N = 1$. Moreover, the number of defect modes is increased by increasing N. So, by tuning them, this structure can be used as a multi-channel filter within an optical wavelength range.

1. INTRODUCTION

When a light source includes light emitted in one direction to 1DPC, it causes transmission and reflection from layers. Optical filters are devices that selectively transmit light of different wavelengths, while blocking the remainder which is called PBG. PBGs have many applications in optical communications, optoelectronics and optical devices [1–3]. A binary PC is a periodic structure including dielectric elements with different refractive indices. There are a lot of researches in using dielectric and metals in PC [4–15].

In this paper, we use transfer matrix method (TMM) to study the behavior of electromagnetic waves inside PC [16–19]. We use this method to 1DPC containing dielectric materials with different refractive indices.

In TMS, the dielectric layers are arranged in THS binary series. The THS structures are well known for their high transmission efficiency which is useful for modeling a multi-channel filter. In this structure by changing the number of defect layers, we can increase the number of resonant peaks very much. Also, the structure of TMS with a defect layer leads to two BGs in both visible and infrared regions, and more defect modes appear in both ranges [20].

2. THEORETICAL ANALYSIS

We use TMS for modeling our proposed filter. TMS is composed of dielectric layers (A and B) with thicknesses d_1, d_2, and their indices of refraction are n_1 and n_2, respectively.

In TMS, we have series as follows

$$S_{n+1} = S_n S_n^* \tag{1}$$

where S_n^* is the complement of S_n. Thus, for calculating S_n^*, we should replace A with B and vice versa. So we have

$$S_1 = AB, \quad S_1^* = BA \tag{1a}$$

$$S_2 = ABBA, \quad S_2^* = BAAB \tag{1b}$$

Received 26 August 2017, Accepted 29 September 2017, Scheduled 25 October 2017

* Corresponding author: Hadis Azarshab (hadis.azarshab@gmail.com).
The authors are with the Department of Physics, Payame Noor University, Tehran, Iran.

And in this way we have,

$$\begin{aligned} S_5 &= (ABBABAABBAABABBABAABBAABBABAAB) \\ S_5^* &= (BAABABBAABBABAABABBAABBAABABBA) \end{aligned} \tag{1c}$$

According formula (1), for modeling filter with 6th generation of TMS we have,

$$S_6 = S_5 S_5^* \tag{2}$$

The defect PC is D^N, where D is dielectric defect layers and N the number of defect layers. According to formula (2) S_6 of TMS is composed of S_5 and S_5^*, and in order to have a multi-channel filter, we add the defect PC between two parts,

$$M_T = S_5 D^N S_5^* \tag{3}$$

So the total characteristic matrix of the PC is given by [10, 21–27]

$$M_T = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}^N = S_5 D^N S_5^*. \tag{4}$$

Then the transmission coefficient (t) is given by

$$t = 2p_0/(m_{11} + m_{12}p_0)p_0 + (m_{21} + m_{22})p_0 \tag{5}$$

where $p_0 = n_c \cos\theta_0$. We can calculate the transmission [21–27].

$$T = |t|^2 \tag{6}$$

Also, the transmission coefficient r by using Equation (4) is given by

$$r = \frac{(m_{11} + m_{12}p_0)p_0 - (m_{21} + m_{22}p_0)}{(m_{11} + m_{12}p_0)p_0 + (m_{21} + m_{22}p_0)} \tag{7}$$

So, we can calculate the reflection $R = |r|^2$.

3. RESULTS AND DISCUSSION

In this paper, layers A and B are InP and Si_3N_4, and their refractive indices and thicknesses are $n_1 = 3.16$, $d_1 = 200$ nm and $n_2 = 2$, $d_2 = 400$ nm. The substrate is assumed to be GaSb with refractive index $n_C = 3.9$. Also, the defect layer is taken to be GaSb whose index of refraction and thickness are $n_D = 3.9$ and $d_D = 600$ nm, respectively. This structure is depicted in Figure 1.

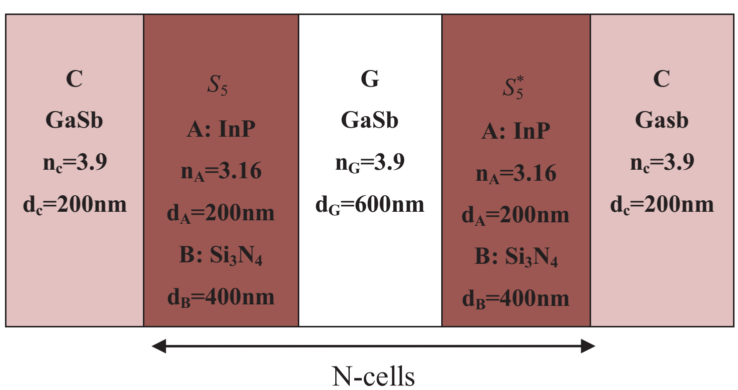


Figure 1. The structure of ternary PC with TMS.

In Figure 2, we show transmission in terms of wavelength in normal incidence without adding a defect layer (Equation (3)). We see that there are two BGs without defect mode for $N = 0$ in visible (between 50 nm to 520 nm) and infrared regions (between 70 nm and 730 nm). So, for modeling a multi-channeled filter, we need to add defect layer D to the structure.

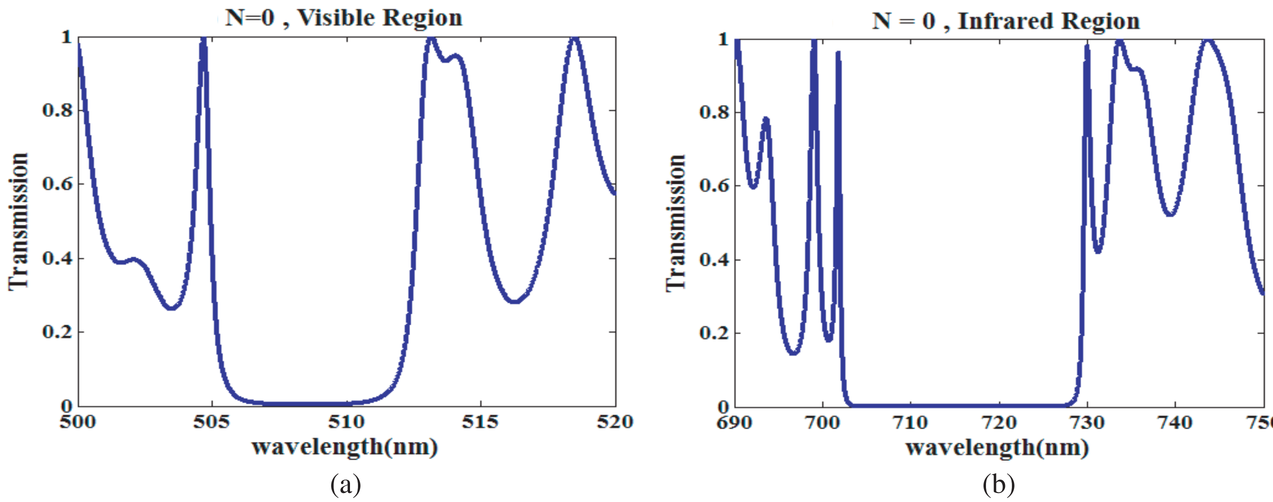
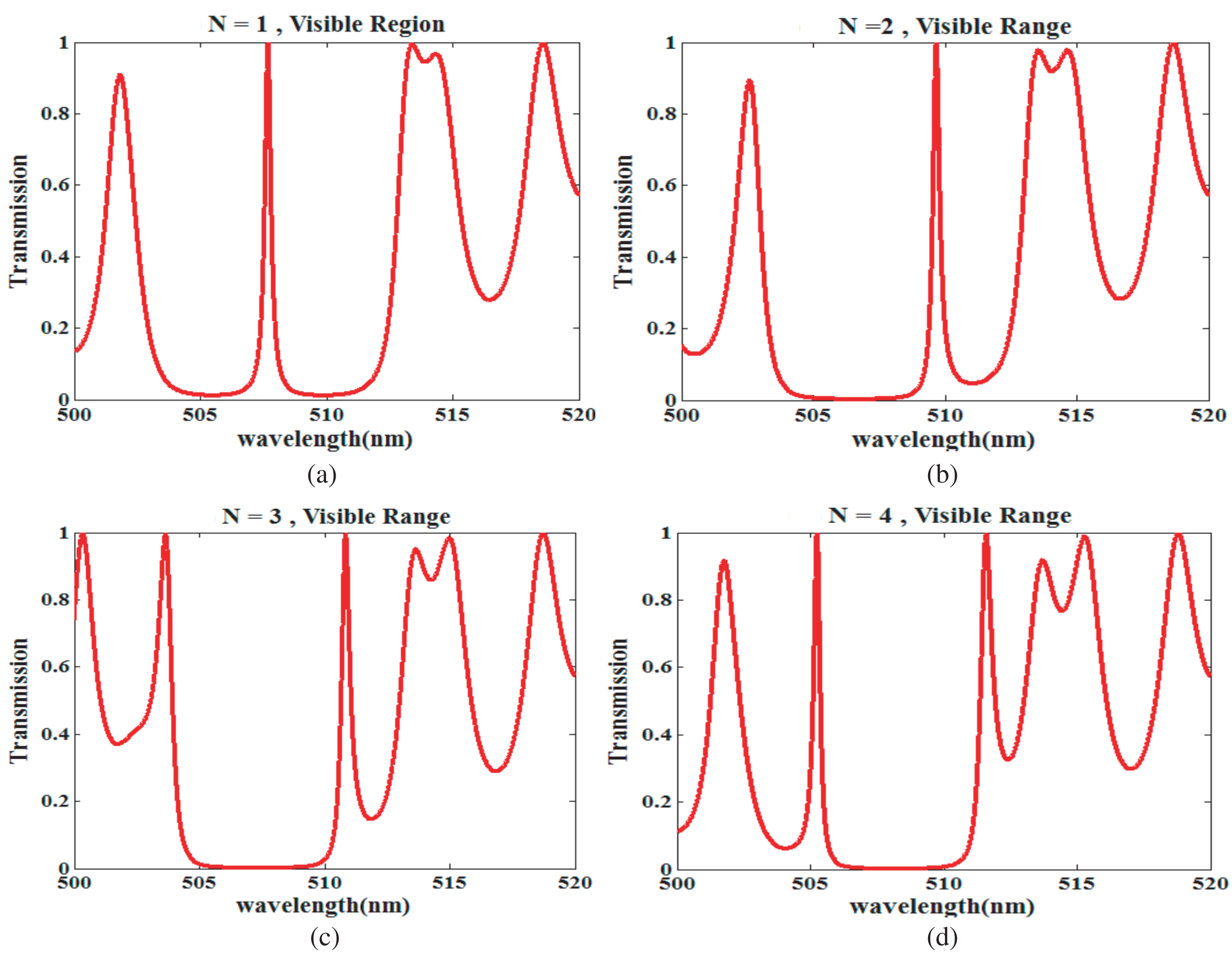
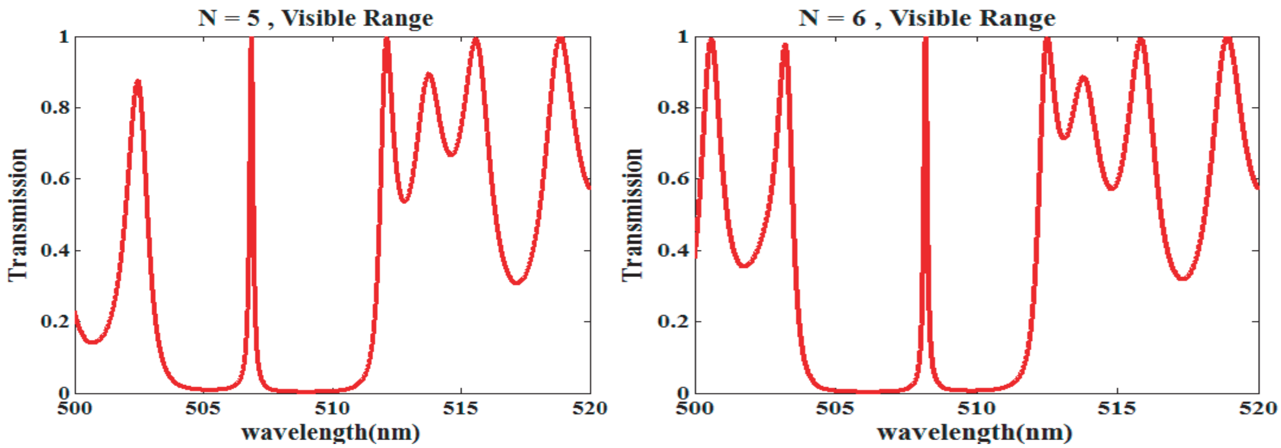


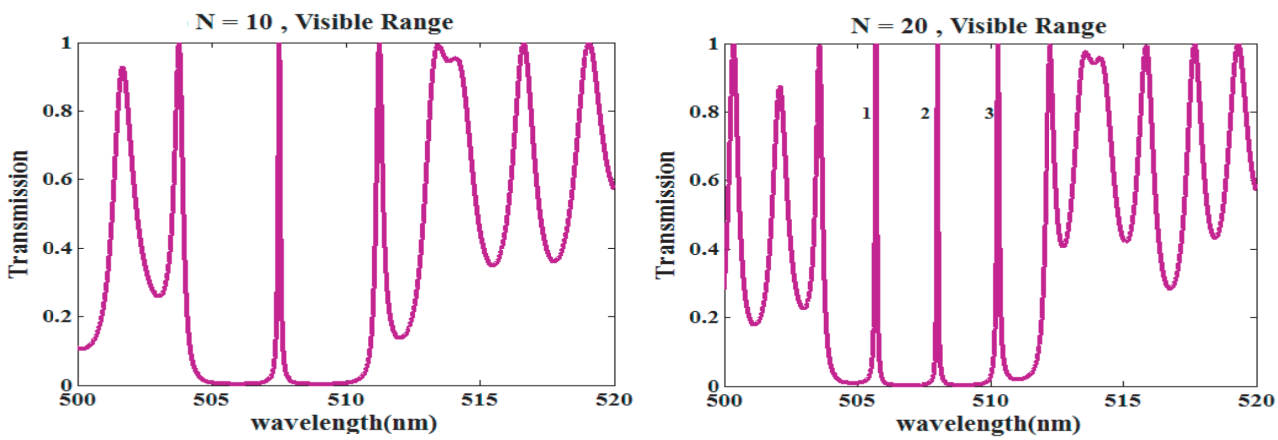
Figure 2. Transmission in terms of wavelength for S_6 (Equation (3)) in normal incidence for (a) visible and (b) infrared region.





(e) (f)

Figure 3. Transmission in terms of wavelength for different N from 1 to 6 in normal incidence in visible range.



(a) (b)

Figure 4. Transmission in terms of wavelength for (a) $N = 10$, (b) $N = 20$ in visible range.

Table 1. The number of defect modes and their wavelengths in 1DPC with THS structure $(C/S_5D^NS_5^*/C)$ in both visible and infrared regions.

N	No. of defect modes	Wavelengths ($\sim$ nm) in visible region	Wavelengths ($\sim$ nm) in infrared region
1	2	507	721
2	2	509	708
3	2	510	720
4	3	505	712–727
5	3	507	706–720
6	3	508	714–726
10	4	507	707–716–724
20	9	505–508–510	703–708–713–717–722–727

In Figure 3, we plot transmission in terms of wavelength for PC with a TMS structure (ABC) and for different numbers of D (Equation (4)). We see that there is one defect mode in visible range, and the number of defect modes is increased by increasing N. We give the wavelength of the defect modes for different N in visible range in Table 1.

In Figure 4, we show transmission in terms of wavelength for higher N. As we see, the number of defect modes increases a lot.

We show transmission in terms of wavelength for different N in infrared region in Figure 5. We see that for the TMS structure in PC we have the other BG in infrared region whose defect modes increase with increasing N. We give the wavelength of the defect modes for different N in infrared range in Table 1.

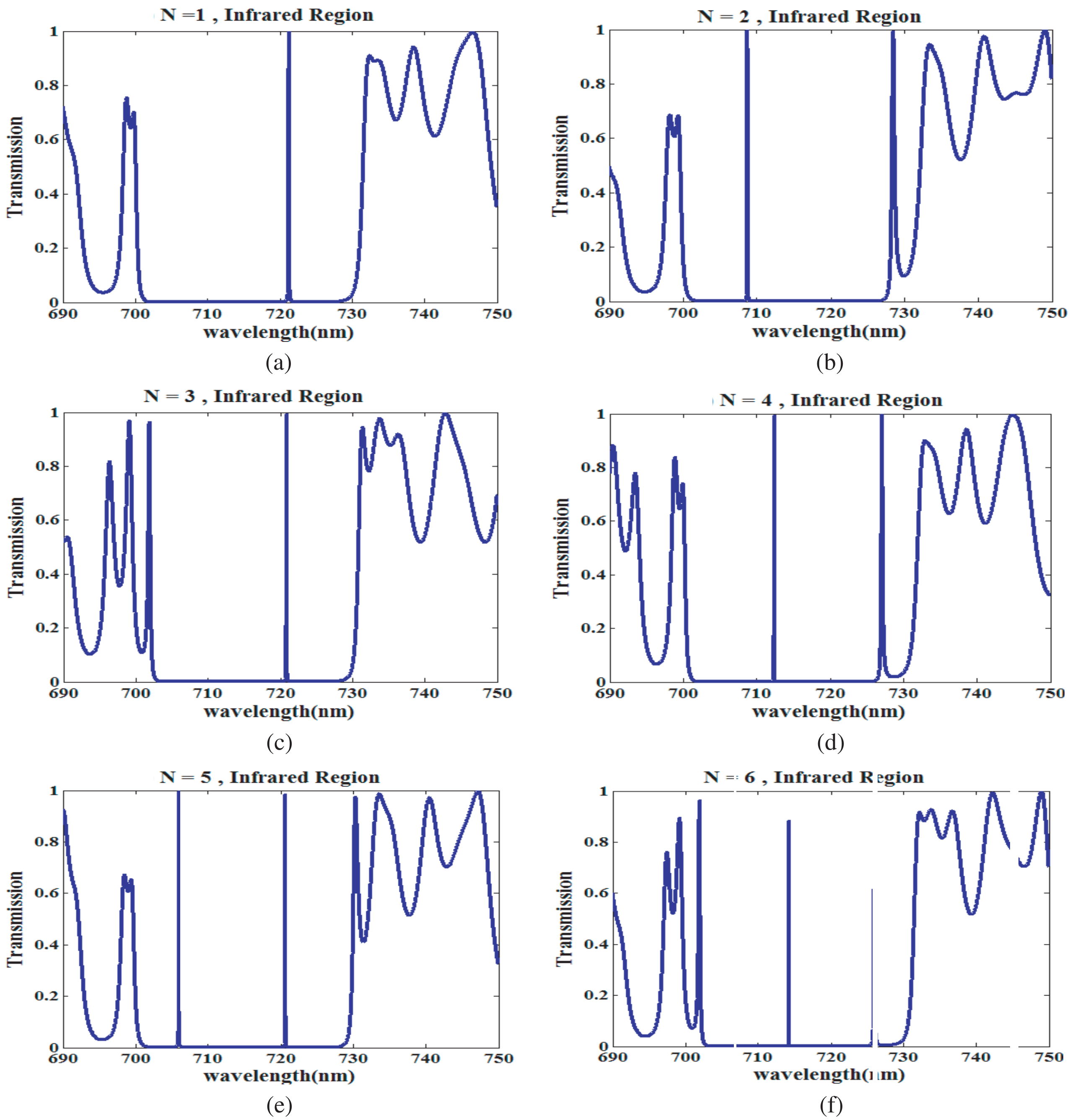
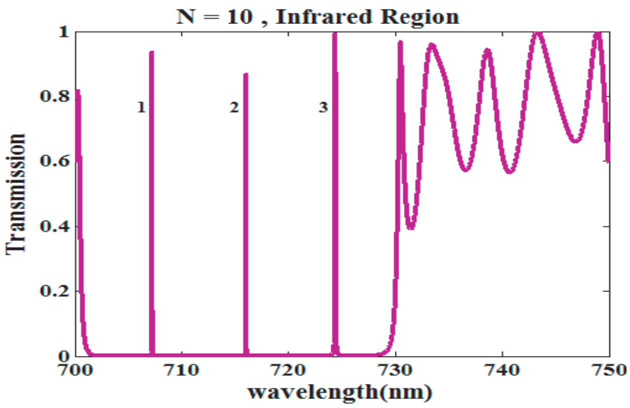
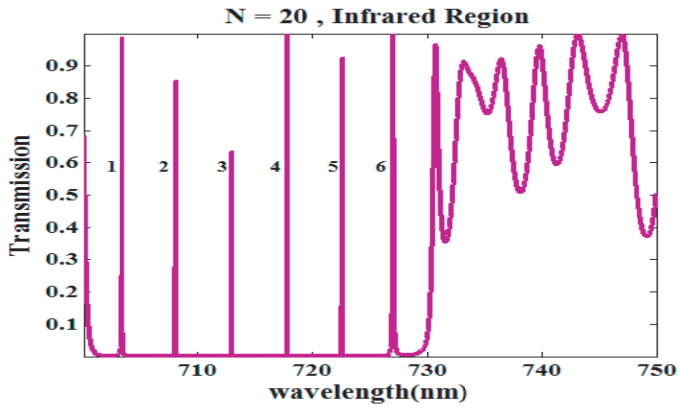


Figure 5. Transmission in terms of wavelength for different N in infrared range.



(a)



(b)

Figure 6. Transmission in terms of wavelength for (a) $N = 10$, (b) $N = 20$ in infrared range.

In Figure 6, we show transmission in terms of wavelength for higher N in infra-red region. As we see, the number of defect modes increases a lot.

4. CONCLUSIONS

In this paper, we have shown that 1DPC with dielectric defect layers based on a TMS structure can act as a multi-channel filter. First, we plot transmission in terms of wavelength for the structure without defect layer (D) and show that there are two PBGs without defect mode. Then, we show transmission in terms of wavelength for different numbers of defect layers (N) in both visible and infrared regions, and we see that there are two defect modes for $N = 1$ in both regions. Also, the number of defect modes increases by increasing N. So, we have more transmission peaks by increasing N. Our analysis shows that 1DPC with TMS structure can be used as a multi-channel filter with high transmission and can be tuned by increasing N.

ACKNOWLEDGMENT

This work has been financially supported by Payame Noor University (PNU) under the Grant of Dr. Gharaati.

REFERENCES

1. Joannopoulos, J. D., R. D. Meade, and J. N. Winn, *Photonic Crystals: Molding the Flow of Light*, Princeton University Press, Princeton, NJ, 1995.
2. Skorobogatiy, M. and J. Yang, *Fundamentals of Photonic Crystal Guiding*, Cambridge University Press, 2009.
3. Sakoda, K., *Optical Properties of Photonic Crystals*, Springer-Verlag, Berlin, 2001.
4. Xu, B., G. Zheng, and Y. Wu, "Narrow band and angle insensitive filter based on one dimensional photonic crystal containing graded index defect," *Mod. Phys. Lett. B*, Vol. 29, 128–136, 2015.
5. Wu, C. J., Y. J. Lee, T. C. King, and W. K. Kuo, "A multichannel filter based on the finite plasma photonic crystal," *Key Engineering Materials*, Vol. 538, 297–300, 2013.
6. Chang, T. W. and C. J. W, "Analysis in a photonic crystal multichannel filter containing coupled defects," *Optik*, Vol. 124, 2028–2032, 2013.
7. Khodadadi, R., "Adjustable filters for optical communications systems based on one-dimensional photonic crystal structures," *International Journal of Engineering Research and Application (IJERA)*, Vol. 2, 272–276, 2012.

8. He, J., P. Liu, Y. He, and Z. Hong, "Narrow bandpass tunable terahertz filter based on photonic crystal cavity," *Optical Society of America*, Vol. 51, 776–779, 2012.
9. Han, P. and H. Z. Wang, "Extension of omnidirectional reflection range in one-dimensional photonic crystals with staggered structure," *J. Opt. Soc. Am. B*, Vol. 20, 1996–2001, 2003.
10. Usievich, B. A., A. M. Prokhorov, and V. A. Sychugov, "A photonic-crystal narrow-band optical filter," *Laser Physics*, Vol. 12, 898–902, 2002.
11. Awasthi, S. K. and S. P. Ojha, "Design of a tunable optical filter by using a one dimensional ternary photonic ban gap material," *Progress In Electromanetics Research M*, Vol. 4, 117–132, 2008.
12. Gharaati, A. and H. Azarshab, "Characterization of defect modes in one-dimensional ternary metallo-dielectric nanolayered photonic crystal," *Progress In Electromanetics Research B*, Vol. 37, 125–141, 2012.
13. Gharaati, A. and H. Azarshab, "Characterization of defect modes in one dimensional binary metallo-dielectric nanolayered photonic crystal," *International Journal of Physics*, Vol. 4, 149–162, 2011.
14. Srivastava, R., K. B. Thapa, S. Pati, and S. P. Ojha, "Omni-direction reflection in one dimensional photonic crystal," *Progress In Electromanetics Research B*, Vol. 7, 133–143, 2008.
15. Azarshab, H. and A. Gharaati, "Analysis of tuning channel filter based on ternary lossy defective metallo-dielectric nano photonic crystal," *Progress In Electromanetics Research Letters*, Vol. 68, 113–119, 2017.
16. Yeh, P., *Optical Waves in Layered Media*, Wiley, New York, 2005.
17. Tang, K., Y. Xiang, and S. Wen, "Tunable transmission and defect mode in one-dimensional ternary left-handed photonic crystal," *Proc. of SPIE*, 60200S.1–60200S, 2005.
18. Skorobogatiy, M. and J. Yang, *Fundamentals of Photonic Crystal Guiding*, Cambridge University Press, 132, 2009.
19. Fan, S., P. R. Villeneuve, and J. D. Joannopoulos, "Large omnidirectional band gaps in metallodielectric photonic crystals," *Phys. Rev. B*, Vol. 54, 11245–11252, 1994.
20. Markos, P. and C. M. Soukoulis, "Wave propagation: From electrons to photonic crystals and left handed materials," Princeton University Press, New Jersey, 2008.
21. Jackson, J. D., *Classical Electrodynamics*, 3rd Edition, 311, California University, 1999.
22. Wu, C. J., Y. H. Chung, and B. J. Syu, "Band gap extension in a one-dimensional ternary metal-dielectric photonic crystal," *Progress In Electromanetics Research*, Vol. 102, 81–93, 2010.
23. Loschialpo, M. J. P. and J. Schelleng, "Photonic band gap structure and transmissivity of frequency-dependant metallic-dielectric systems," *J. Appl. Phys.*, Vol. 88, 5785–5790, 2000.
24. Topasna, D. M. and G. A. Topasna, "Numerical modeling of thin film optical filters," *Education and Training in Optics and Photonics (ETOP)*, 230–239, July 5, 2009.
25. Malaviya, S. K. U. and S. P. Ojha, "Enhancement of omnidirectional total-reflection wavelength ranges by using one-dimensional ternary photonic bandgap material," *J. Opt. Soc. Am. B: Optical Physics*, Vol. 23, 2566–2571, 2006.
26. Born, M. and E. Wolf, *Principles of Optics*, Cambridge, London, 1999.
27. Saleh, B. E. A. and M. C. Teich, *Fundamentals of Photonics*, Wiley, New York, 2007.