Novel Design of Optical Channel Drop Filter Based on Photonic Crystal Ring Resonators

Zohreh Rashki, Seyed Javad Seyed Mahdavi Chabok
Department of Electrical Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran
zohrehrashki@mshdiau.ac.ir, mahdavi@mshdiau.ac.ir
Corresponding author: *zohrehrashki@mshdiau.ac.ir*

***Abstract*— In this paper, a new design of optical channel drop filter based on two- dimensional photonic crystal ring resonators with triangular lattice is proposed. The rods of this structure is silicon with the refractive index 3.46 and the surrounding environment is air with the refractive index of 1.The widest photonic band gap obtained is for filling ratio of *r/a = 0.2.* The filter's transmission spectrum is calculated using the two-dimensional (2D) finite-difference time-domain (2D-FDTD) numerical method. The simulation shows 100% dropping efficiency and suitable quality factor at 1519.4 *nm* wavelength achieved for this filter. Also, in this paper, we investigate parameters which have an effect on resonant wavelength and transmission spectrum in this CDF, such as refractive index of inner rods and whole of dielectric rods of the structure. The overall size of the structure is small that is 14 µm × 14µm which is suitable for photonic integrated circuits (PIC) and optical communication network applications.**

***Index Terms*—**Photonic crystal, Ring resonator, Triangular lattice, Optical communication.

I. INTRODUCTION

During the recent century, the scientific and research communities were trying to control the electric features of materials. Development in semiconductive material caused organization of conductive features of certain material which was started with transistor revolution in electronics. In the current decade, the focus is on controlling optical features of the material [1].

To date, developing high speed telecommunication, the demand for data transfer and process with higher paces and integrated technology, using all optical wares are inevitable in most of electronic and communication fields. According to the weaknesses of electronic integrated circuits, such as processing speed and data transfer, the size and increasing working frequency, the scholars in this scientific field think of replacing optical integrated circuits with electronic integrated circuits. In optical integrated circuits, photon is used as data carrier. We prefer to use optical integrated circuits instead of electronic integrated circuits, they are: higher data processing and data transfer rate, very smaller circuits, higher working frequency and so much lower noise and etc [2]. Since 1987, the

Manuscript received 6-Jan.-2015 and revised 12-April-2015,
Accepted on 26- May-2015
P- ISSN: 2322-4088
E- ISSN: 2322-3936

science of using Photonic crystals is rapidly developing and receives special attention by the scientific and research communities because of their numerous and invaluable nonlinear applications in sensor and communication fields[3]. Photonic crystals(PhCs) are very suitable candidates for realization of future passive and active optical devices because of their ability to control light-wave propagation, high speed of operation, better confinement, long life period and suitability for photonic integrated circuits (PIC) and optical communication network applications [4, 5]. PhCs are periodic optical nanostructures composed of two different materials with low and high dielectric constant [2, 5] As a result of this periodicity, it possesses photonic band gap (PBG), where the transmission of light in certain frequency range is absolutely zero [6]. Depending on geometry of the structure, PhCs can be divided into three broad categories, namely one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) structures. 2D PhCs due to their complete PBG and ease of design and fabrication attract more attention than1D and 3D structures [7].In 1996, Thomas Krauss [6], made two dimensional photonic crystals for the frequencies near to infrared spectrum for the first time . In recent years, many of optical devices made were based on PhCs. i.e. multiplexers [6], demultiplexers [8], polarization beam splitters [9], triplexers [10], switches [11], directional couplers [12], bandpass filters [13-15], add - drop optical filters and channel drop filters [16-23], etc. A Waveguide-coupled ring resonator provides an ideal basic structure for channel drop (or add-drop) filters. Also, this structure is exceedingly beneficial components for switching, modulation, and multiplexing/demutliplexing tasks in photonic integrated circuits (PICs) [23]. Photonic crystal ring resonators are new kinds of cavity defects which their size is determined by the desired resonant wavelength, and the tradeoff between the cavity Q and the modal volume. The ring resonators also can be used to realize optical switches, optical sensors, di-multiplexers and etc. [4]. During recent years, the channel drop filters and optical add-drop filters are presented based on photonic crystals ring resonators (PCRR).The first PCRR in photonic crystal structures in Laser cavity in the hexagonal lattice was introduced by Kim et al. which the flexibility and effective distribution were investigated [24]. Later, the spectral characteristics of the waveguide-coupled rectangular ring resonators in photonic crystals were investigated by Kumar et al. [25]. Up to now several PCRR's are illustrated in the photonic crystal structures [4, 23, 26]. Recently two types of different structures are presented by Mahmood et al to design channel drop filters using ring resonators [27, 28, 29].

In the present study, a new design of PCRR based channel drop filters (CDFs) is proposed and analyzed. The introduced ring resonators in the study can be used as a crucial element for other optical device. The PWE method is the most popular method to calculate the band gap of the structure. The 2D-FDTD method has been used to obtain the wavelength response of the CDF. Both PWE and FDTD are simulated by Bandsolve and Full wave simulators of Rsoft.

In the second part the research, the calculations on band structure and designation of structure are explained and in the third part, simulation results and the effects of changes refractive index on the

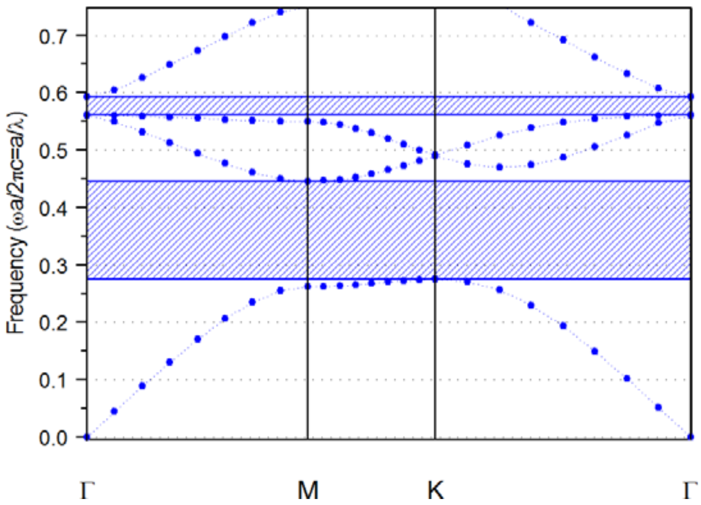


Fig. 1. Band structure of triangular lattice photonic crystal of TM polarized light.

output frequency and transmitting spectrum from the CDF are described and finally as the last part, we will present the conclusion.

II. STRUCTURE DESIGN

The design in this paper is based on two-dimensional (2D) triangular lattice of silicon rods with refractive index $n_{Si} = 3.46$ in an air background with $n_{air} = 1.00$. Also the number of rods in the plate x-z is equal to 23×23. In this investigation, the ratio of the rod radius r to the lattice constant *a*, is 0.2. which is *a* lattice constant (the distance between the centers of two adjacent rods). 2-D PWE methods are employed to estimate the triangular lattice photonic band gap of TM polarized light as shown in Fig. 1. The PWE method is the most popular method to calculate the band gap of the structure which has been used for calculating the PBG with and without introducing any defects. In this structure, wider photonic band gap extends for the normalized frequency $0.27 < a/\lambda < 0.45$ for TM polarization ,where λ is the wavelength in free space.

III. PHOTONIC CRYSTAL RING RESONATOR

Today, using ring resonators to design optical device receive more attention compared to point and linear defects among the researchers because ring resonators offer scalability in size, flexibility in mode design due to their multi-mode nature and adaptability in structure design because of numerous design parameters [23]. These parameters can be the radius of the scatterers, coupling rods and the dielectric constant of the structure. Recently, several types of CDF based on 2D PCRR have been proposed using quasi-square PCRR, square PCRR, dual square PCRR [30], dual curved PCRR [20], hexagonal PCRR [31], 45° PCRR [32], circular PCRR [33] and X-shaped ring resonator structure[29].

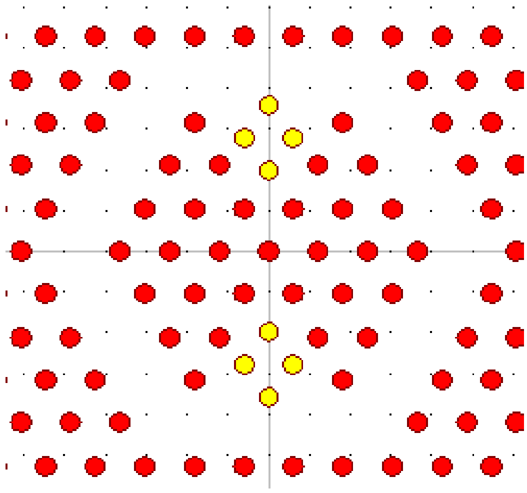


Fig. 2. Schematic structure of PCRR

The ring resonators presented in this study is a new design from photonic crystal ring resonators compared to the previous ring resonators presented in different articles.

Fig. 2 shows the designed ring resonators structure in this article. Eight additional extra scattering rods with yellow color are introduced to improve the spectral selectivity and obtain a very high dropped efficiency [34]. These scatterers have exactly the same refractive indexes as all other dielectric rods in PhC structure and their diameters is chosen to be $r_S = 0.965*r$ for better performance.

IV. SIMULATION RESULTS AND DISCUSSION

Optical filters are one of the most important building blocks of optical communication networks which play a crucial role in wavelength division multiplexing (WDM) technologies. Optical filters can be used for separating nearly spaced optical channels from each other in WDM applications. Recently different mechanisms have been proposed for performing filtering behavior based on PhC structures. Defect structures, resonant cavities coupled waveguides and ring resonators [32] are some examples of proposed filtering mechanisms. In general, a ring resonator is positioned between two optical waveguides provides an ideal basic structure for CDF such that power in one waveguide is transferred into the other through the resonance of the ring, which is used to add or remove a channel from the multiplexed input/output signals. Fig. 3 shows the schematic structure of CDF. It consists of two waveguides(bus and dropping waveguides) and a PCRR between them(coupling element).Also, it has four ports, among them ports A and B are the input and transmission output terminals whereas ports C and D are forward and backward dropping terminals, respectively. A Gaussian input signal is launched into the port A. The normalized transmission spectra are obtained at ports ‘B’, ‘C’ and ‘D’ by conducting Fast Fourier Transform (FFT) of the fields that are calculated by 2D FDTD method. The input and output signal power is recorded by power monitors which are positioned at the input

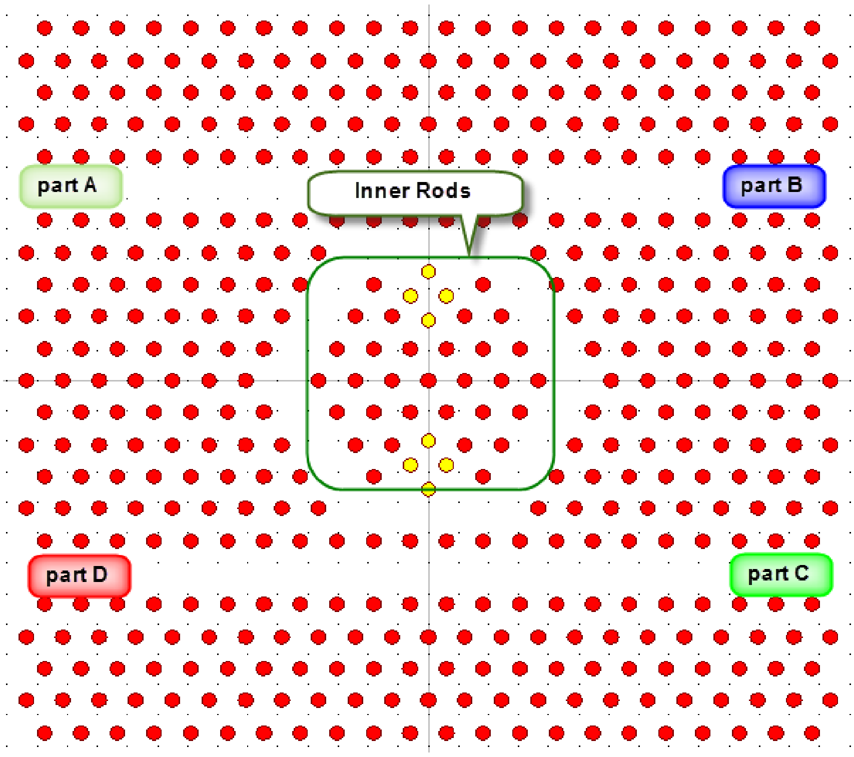


Fig. 3. Schematic diagram of the CDF.

and output ports. The CDF responses are simulated using the 2D-FDTD method [33].

The 2D- FDTD method has been used to obtain the wavelength response of the CDF. The normalized transmission spectra at ports B, C and D are displayed in Fig. 4. As shown in Fig. 4, perfect channel drop operation from the input terminal to the forward drop terminal through the resonant ring is observed. At resonance, the propagating waveguide mode couples to the resonant modes of the PCRR cavity. Thus, all the power in the bus waveguide is extracted by using resonant tunneling process and transferred into the drop waveguide. Note that the system can perform backward dropping operation by further tuning such as the radius of the rods, the radius of colored rods and/or the refractive index of whole rods. 100% forward dropping efficiency is achieved while the operating wavelength is 1519.4 *nm*. The value of *Q* for the proposed structure is obtained 189.87. *Q* factor can be calculated with $Q = \lambda/\Delta\lambda$, where λ and $\Delta\lambda$ are central wavelength and full width at half power of output, respectively.

According to comparisons of the new design of CDF and the similar articles, the different features of this filter are higher quality factor and higher spectral selectivity. This comparison is done in Table 1, in which the drop efficiency of the proposed structure is100% at the wavelength of 1519.4 *nm*.

Table 1. Comparing devices based on PCRRs available in a variety of papers.

Reference	Dropping efficiency (%)	Quality factor	PCRR type
This paper	100	189.87	Diamond
Djavid et al. [4, 35]	99	52.7	Quasi-square
Qiang et al. [36]	99	160	Quasi-square
Robinson and Nakkeeran [26, 37, 38]	100	128, 114.6	Circular

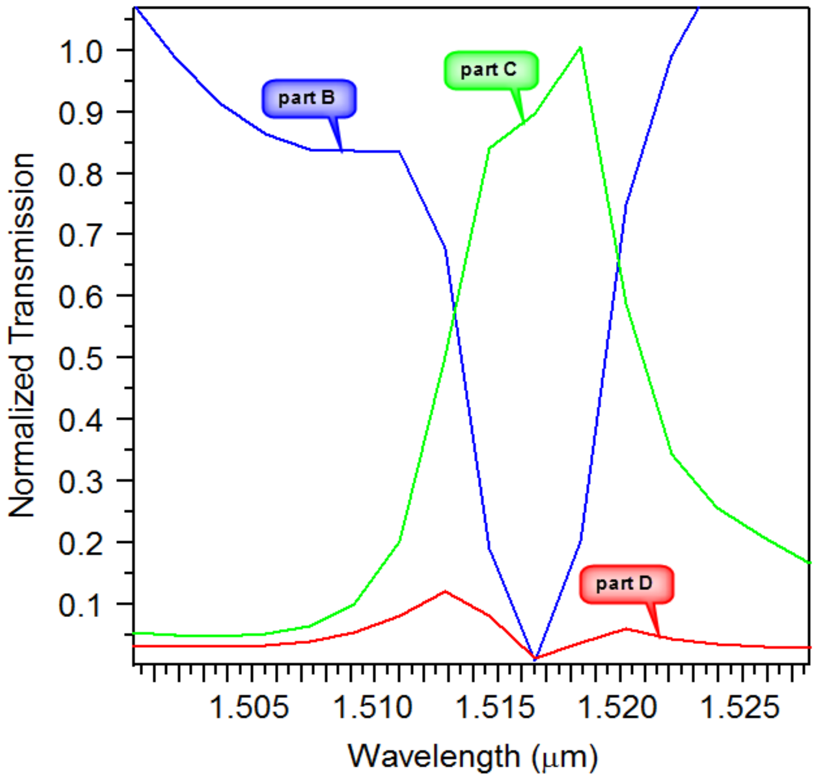
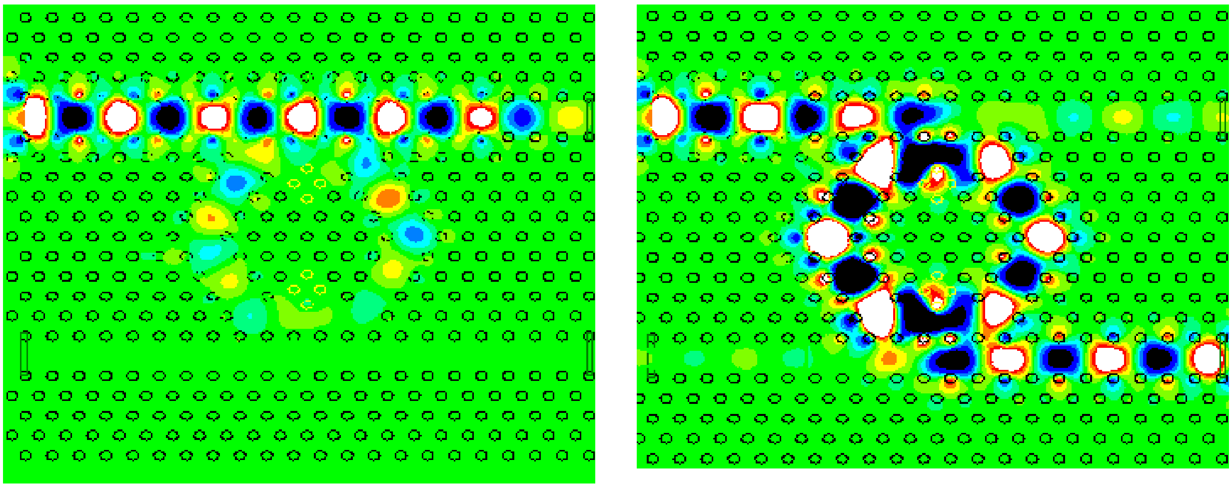


Fig. 4. Transmission spectra of the CDF at ports B, C and D respectively.

One of the most important features of any filter is its tune ability. In next sections, the effect of varying some parameters on ring resonator performance will be studied. Section **A** describes the effect of varying refractive index of rods and Section **B** describes the effect of varying the refractive index of inner rods.



(a) (b)

Fig. 5. Electric field pattern of the ring resonator at (a) 1501.4 *nm* (non-resonant wavelength) and (b) 1519.4 *nm* (resonant wavelength).

A. Varying the refractive index of rods

First parameter we are going to investigate is the refractive index of dielectric rods. we assume all other parameters such as radius of rods and refractive index of inner rods to be constant. Then obtain the output spectra of the filter for different values of refractive index. Different values of refractive index are chosen of article Alipour-Banaeia et al [39]. The output spectra of the filter for six different values of refractive index are shown in Fig. 6. Six different curves are displayed in Fig. 6 for $n_1 = 3.4$, $n_2 = 3.42$, $n_3 = 3.44$, $n_4 = 3.46$, $n_5 = 3.48$ and $n_6 = 3.5$.

As seen in Fig. 6, the proposed structure, when simulated with the different refractive index equal to for $n_1 = 3.4$, $n_2 = 3.42$, $n_3 = 3.44$, $n_4 = 3.46$, $n_5 = 3.48$ and $n_6 = 3.5$, can select wavelengths $\lambda_1 = 1511.5$ *nm*, $\lambda_2 = 1513.8$ *nm*, $\lambda_3 = 1515.8$ *nm*, $\lambda_4 = 1519.4$ *nm*, $\lambda_5 = 1521.3$ *nm* and $\lambda_6 = 1524.6$ *nm*, respectively. As shown in Fig. 6, by raising the refractive index, the resonant wavelength of the device is increased accordingly. In other words, a red shift occurs in resonant wavelength.

B. Varying the refractive index of inner rods

With localized change in inner rods' refractive index, the resonant wavelength can be tuned. This leads to a tunable CDF. Fig. 7 shows the normalized power transmissions of the structure with three different refractive index of inner rods, $n_1 = 3.11$, $n_2 = 3.31$, $n_3 = 3.39$, $n_4 = 3.60$. Different values of refractive index are chosen based on article by Robinson et al. [26].

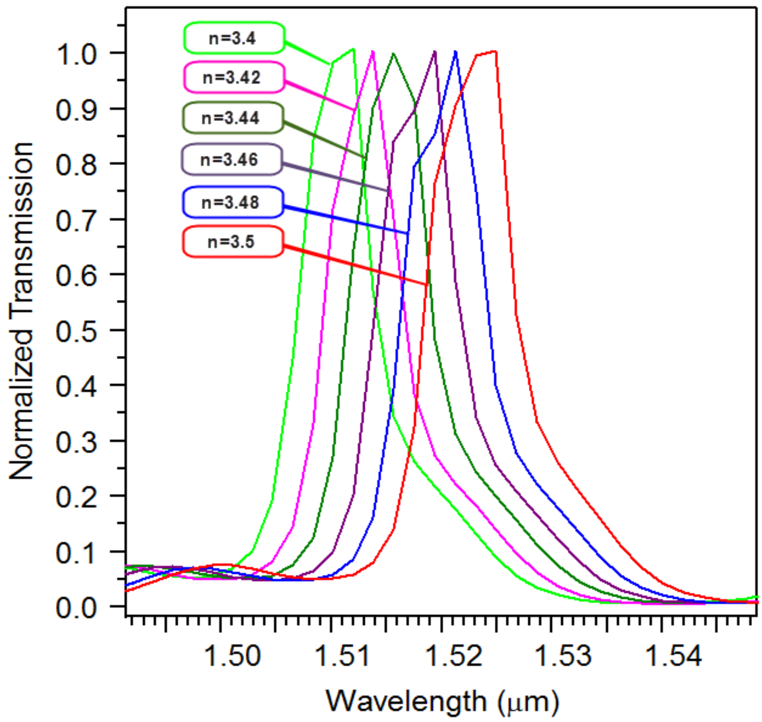


Fig. 6. Normalized power transmission spectra of the proposed CDF for different values of refractive index of of dielectric rods.

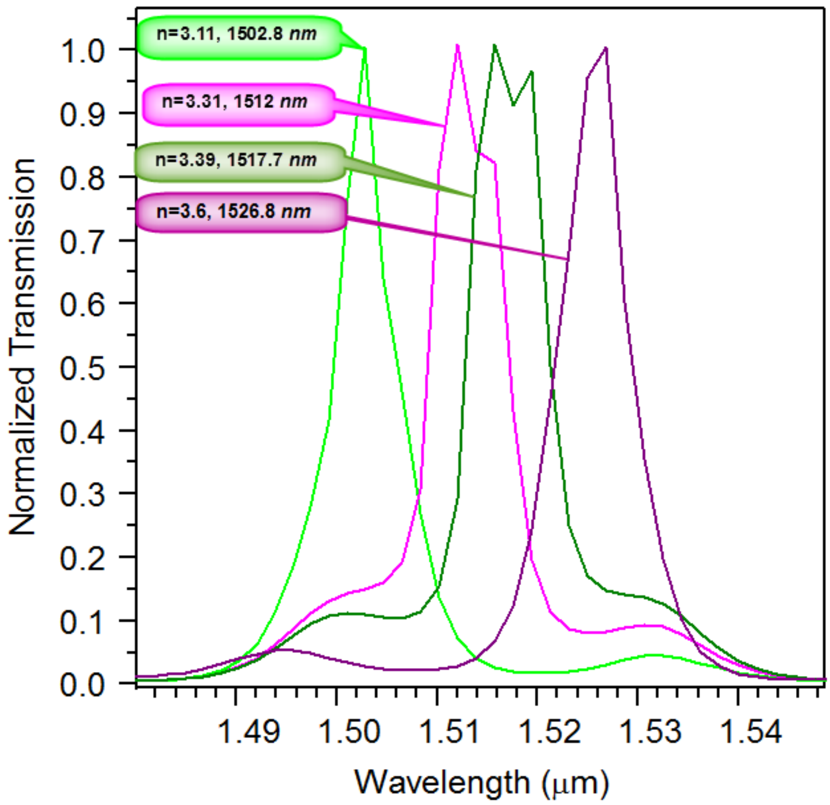


Fig. 7. Normalized power transmission spectra of the proposed CDF for different values of different values of refractive index of inner rods

V. CONCLUSIONS

In this paper, a new design of channel drop filter in triangular lattice PhC silicon rods using PCRRs was proposed. The proposed filter has a resonant wavelength at 1519.4 nm with transmission efficiency equal to 100% and suitable quality factor. The impact of varying the dielectric constant of rods on the output wavelength of the filter has been studied. By raising the refractive index, the resonant wavelength of the device is increased accordingly. It was shown that the resonance wavelength of CDF has been tuned by varying this parameter appropriately.The suggested CDF is compact and the overall size of the chip is about 14 μm × 14 μm. Hence, this kind of devices would be more useful to realize circuits of integrated optics for CWDM systems and other nanophotonic structures.

REFERENCES

[1] J. D. Joannopoulos, S.G. Johnson, J.N. Winn, and R.D. Meade, Photonic, Crystals: Molding the Flow of Light, 2nd Ed., Princeton University Press, 2008.

[2] H. Debrégeas-Sillard, Ch. Kazmierski, “Challenges and advances of photonic integrated circuits,” *Comptes Rendus Physique,* vol. 9, issue 9-10, pp. 1055–1066, Nov. 2008.

[3] A.Ghanbari, A. Kashani Nia ,A.Sadr, “Square Lattice Elliptical Core Photonic Crystal Fiber Soliton-Effect Compressor at 1550nm, ” Journal of Communication Engineering, Vol. 4, No. 1, Jan.June 2015.

[4] M. Djavid, M.S. Abrishamian, “Multi-channel drop filters using photonic crystal ring resonators,” *Optik-International Journal for Light and Electron Optics*, vol. 123, issue 2, pp. 167– 170, Jan. 2012.

[5] H. Alipour-Banaeia, S. Serajmohammadib, F. Mehdizadehc, “All optical NOR and NAND gate based on nonlinear photonic crystal ring resonators,” *Optik-International Journal for Light and Electron Optics, vol.* 125, issue 19, pp. 5701–5704, Oct. 2014.

[6] T. F. Krauss, R. M. De La Rue, S. Brand, “Two-dimensional photonic-band gap structures operating at near-infrared wavelengths,” *Nature,* vol. 383, no. 6602, pp. 699-702, 1996.

[7] G. Manzacca, D. Paciotti, A. Marchese, M.S. Moreolo, G. Cincotti, “2D photonic crystal cavity-based WDM multiplexer,” *Photonics and Nanostructures – Fundamentals and Applications*, vol. 5, pp. 164–170, 2007.

[8] A. Ghaffari, F. Monifi, M. Djavid, M.S. Abrishamian, “Heterostructure wavelength division demultiplexers using photonic crystal ring resonators,” *Optics Communications*, vol. 281, issues 15-16, pp. 4028–4032, 2008.

[9] V. Zabelin, L.A. Dunbar, N. Le Thomas, R. Houdre, M.V. Kotlyar, L. O’Faolain, T.F. Krauss, “Self-collimating photonic crystal polarization beam splitter,” *Optics Letters*, vol. 32, issue 5, pp. 530–532, 2007.

[10] T. T. Shih, Y. D. Wu, J. J. Lee, “Proposal for compact optical triplexer filter using 2-D Photonic crystals,” *IEEE Photonics Technology Letters*, vol. 21, issue 1, pp. 18–21, 2009.

[11] Q. Wang, Y. Cui, J. Zhang, C. Yan, L. Zhang, “The position independence of heterostructure coupled waveguides in photonic-crystal switch,” *Optik–International Journal for Light and Electron Optics*, vol. 121, issue 8, pp. 684–688, 2010.

[12] M. K. Moghaddam, A. R. Attari, M. M. Mirsalehi, “Improved photonic crystal directional coupler with short length,” *Photonics and Nanostructures - Fundamentals and Applications,* vol. 8, issue 1, pp. 47–53, 2010.

[13] F. Monifi, M. Djavid, A. Ghaffari, M.S. Abrishamian, “A new bandstop filter based on photonic crystals,” *PIERS Proceedinbgs*, pp. 674–677, July 2008.

[14] R. Costa, A. Melloni, M. Martinelli, “Bandpass resonant filters in photonic-crystal waveguides,” *IEEE Photonics Technology Letters,* vol. 15, no. 3, pp. 401–403, 2003.

[15] J. Barvestani, “Omnidirectional narrow bandpass filters based on one-dimensional superconductor–dielectric photonic crystal heterostructors,” *Physica B: Condensed Matter*, vol. 457, 218–224, Jan. 2015.

[16] C. C. Wang, L. W. Chen, “Channel drop filters with folded directional couplers in two-dimensional photonic crystals,” *Physica B: Condensed Matter*, vol. 405, issue 4, pp. 1210–1215, 2010.

[17] S. Robinson, R. Nakkeeran, “Channel drop filter based on 2D square-lattice photonic crystal ring resonator,” *7th IEEE International Conference on WOCN’10,* Sri Lanka, September 6–8, 2010.

[18] J. J. Vegas Olmos, M. Tokushima, K. Kitayama, “Photonic add–drop filter based on integrated photonic crystal structures,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 16 , issue 1, pp. 332–337, 2010.

[19] B. Saghirzadeh Darki, N. Granpayeh, “Improving the performance of a pho-tonic crystal ring-resonator- based channel drop filter using particle swarm optimization method,” *Optics Communications*, vol. 283, issue 20, pp. 4099–4103, Oct. 2010.

[20] P. Andalib, N. Granpayeh, “Optical add/drop filter based on dual curved photonic crystal resonator,” *5th IEEE International Conference on Photonics,* pp. 249–250, 2008.

[21] M. David, A. Ghaffari, F. Monifi, M.S. Abrishamian, “T-Shaped channel drop filters using photonic crystal ring resonators,” *Physica E: Low-dimensional Systems and Nanostructures*, vol. 40, issue 10, pp. 3151–3154, Sept. 2008.

[22] M. R. Rakhshani, M. A. Mansouri-Birjandi, “Realization of tunable optical filter by photonic crystal ring resonators,” *Optik - International Journal for Light and Electron Optics,* vol. 124, issue 22, pp. 5377–5380, Nov. 2013.

[23] H. Alipour-Banaei, F. Mehdizadeh, M. A. Hassangholizadeh-Kashtiban, “New proposal for PCRR-based channel drop filter using elliptical rings,” *Physica E: Low-dimensional Systems and Nanostructures*, vol. 56, pp. 211–215, Feb. 2014.

[24] S. H. Kim, H. Y. Ryu, H. G. Park, G. H. Kim, Y. S. Choi, Y.H. Lee. “Two-dimensional photonic crystal hexagonal waveguide ring laser,” *Applied Physics Letters,* vol. 81, pp. 2499–2501, 2002.

[25] V. Dinesh Kumar, T. Srinivas, A. Selvarajan, “Investigation of ring resonators in photonic crystal circuits,” *Photonics and Nanostructures - Fundamentals and Applications*, vol. 2, issue 3, pp. 199–206, Dec. 2004.

[26] S. Robinson and R. Nakkeeran, “PCRR based add drop filters using photonic crystal ring resonators,” *Optik-International Journal for Light and Electron Optics*, 2012.

[27] M. Youcef Mahmoud, G. Bassou, F. Metehri, “Channel drop filter using photonic crystal ring resonators for CWDM communication systems,” *Optik-International Journal for Light and Electron Optics*, vol. 125, issue 17, pp. 4718–4721, Sept., 2014.

[28] M. Y. Mahmoud, G. Bassou, A. Taalbi, “A new add-drop filter based on two dimensional photonic crystal ring resonator,” *Optik-International Journal for Light and Electron Optics*, vol. 124, issue 17, pp. 2864–2867, Sept. 2013.

[29] M. Y. Mahmoud, G. Bassou, A. Taalbi, Z.M. Chekroun, “Optical channel drop filters based on photonic crystal ring resonators,” *Optics Communications*, vol. 285, pp. 368–372, 2012.

[30] J.B. Bai, J.Q. Wang, X.Y. Chen, J.Z. Jiang, L. Hui, Y.S. Qiu, Z.X. Qiang, “Characteristics of 45◦ photonic crystal ring resonators based on square-lattice silicon rods, ” Optoelectron. Lett. 6 ,0203–0206, 2010.

[31] S. Robinson, R. Nakkeeran, “Photonic crystal ring resonator based add-drop filter using hexagonal rods for CWDM systems,” Optoelectronics Letters, vol. 7, pp. 164–166, May 2011.

[32] J.B. Bai, J.Q. Wang, X.Y. Chen, J.Z. Jiang, L. Hui, Y.S. Qiu, Z.X. Qiang, “Characteristics of 45◦ photonic crystal ring resonators based on square-lattice silicon rods, ”Optoelectron. Lett. 6 ,0203–0206, 2010.

[33] K. Venkatachalam D. Sriram Kumar S. Robinson, “Performance analysis of 2D-Photonic Crystal based Eight Channel Wavelength Division Demultiplexer, ” Optik ,Vol 127, 8819–8826,2016.

[34] J. Jun-zhen, Q.Ze-xuan, Z. Hao, Z. Yan,and Q. Yi-shen. “ A high-drop hole-type photonic crystal add-drop filter, ” Vol.10 No.1, 1 January 2014.

[35] A. Ghaffari, F. Monifi, M. Djavid, M.S. Abrishamian, “Photonic crystal bends and power splitters based on ring resonators,” Optics Communications, vol. 281, issue 23, pp. 5929–5934, Dec. 2008.

[36] Z. Qiang, W. Zhou, R.A. Soref, “Optical add-drop filters based on photonic crystal ring resonators,” *Optics Express*, vol. 15, issue 4, pp. 1823–1831, 2007.

[37] S. Robinson, R. Nakkeeran, “Performance evaluation of PCRR based add dropfilter with different rod shapes,” *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, vol. 11, issue 1, 2012.

[38] S. Robinson, R. Nakkeeran, “Investigation on parameters affecting the performance of two dimensional photonic crystal based bandpass filter,” *Optical and Quantum Electronics*, vol. 43, issue 6, pp. ,69–82, March 2012.

[39] H. Alipour-Banaei, M. Jahanara, F. Mehdizadeh, “T-shaped channel drop filter based on photonic crystal ring resonator,” *Optik-International Journal for Light and Electron Optics*, vol. 125, issue 18, pp. 5348-5351, Sept. 2014.