A New Proposal for PCRR- Based Optical Channel Drop Filter

Zohreh Rashki[1], Seyyed Javad SeyyedMahdavi Chabok[2]
1- Department of Electrical Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran.
Email: zohrehrashki@mshdiau.ac.ir (Corresponding author)
2- Department of Electrical Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran.
Email: mahdavi@mshdiau.ac.ir

Received: January 2017 Revised: January 2017 Accepted: January 2017

ABSTRACT:
Ring resonators are useful elements especially in channel drop filters. A novel configuration of photonic crystal ring resonators(PCRRs) based on optical channel drop filters (CDFs) with triangular lattice is proposed. The rods of this structure is silicon with the refractive index n_{si}=3.46 and the surrounding environment is air with the refractive index of n_{air}=1. The widest photonic band gap obtains for the filling ratio of r/a = 0.2. The normalized transmission spectra of CDF are observed using Two- Dimensional-finite difference time domain (2D-FDTD) method. The photonic band gap (PBG) is calculated by plane wave expansion (PWE) method. The simulation shows, 100% dropping efficiency and suitable quality factor at 1534.5*nm* wavelength achieved for this filter. Also in this paper, we investigate parameters which have an effect on resonant wavelength and transmission spectra in this CDF, such as refractive index of inner rods and the refractive index of whole rods of the structure. The area of the proposed structure is about 10.32µm × 10.32µm which is suitable for photonic integrated circuits and optical communication network applications.

KEYWORDS: photonic crystal, ring resonators, triangular lattice, photonic integrated circuits, optical communication.

1. INTRODUCTION

Optical communication is one of the greatest successes people achieved in the last century. It provides an excellent solution for the flow of information. The explosive expansion of Internet services has led to a transformation from "telecommunication" to "data communication". The digital data traffic has been doubling every half-year. To support this revolution, fiber-optic communication technologies have developed rapidly because it could offer much higher speed and larger capacity.

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 science of using Photonic crystals is rapidly developing and receives special attention by the scientific and research communities.

Photonic crystals (PCs) channel drop filters (CDFs) have been engineered and fabricated owing to their compact and integrated characteristics. Because they have the potential applications in photonic integrated circuits (PICs) and dense wavelength division multiplexing (DWDM) optical communication systems, the researches have been focused in the areas [3], [4]. Photonic crystals can have both a very high quality factor and an extremely small modal volume. Photonic crystals (PCs) with periodic dielectric materials have provided new ways of controlling light by means of photonic band gap (PBG). The PBG is a frequency gap where the transmission of light in certain frequency range is absolutely zero [5], [6].This feature, in turn, has been utilized for realization of new optical functionalities and many novel devices. Recent years, PCs 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 integration[7], [8]. By creating the defects (point or line) in the periodic structure, it is possible to guide the propagation of light through the PBG region. This peculiar behaviour can lead to realize almost all kinds of PC based active and passive optical devices [9]. Various optical components can be realized by introducing the defects in the PC structures such as multiplexers[10], demultiplexers [11-12], polarization beam splitters [13], triplexers [14], switches[15], directional couplers[16], bandpass filters, channel drop filters/add-drop filters [17–26].

Nowadays, all-optical CDFs are the basis of wavelength division multiplexer telecommunication systems. On the other hand, compactness is an important issue for future all-optical integrated circuits. Hence, one of the most important candidates for constructing ultra small CDFs without significant losses are photonic crystal ring-resonators (PCRRs), where the guided mode is coupled between two waveguides. A variety of structures have been proposed for designing all optical PhC based filters such as defective multilayers, quasi crystal defects, resonant cavities, and ring resonators [27].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 [28,29]. These parameters can be the radius of the scaterers, coupling rods and the dielectric constant of the structure. The ring' model presented in this study is different compared to the previous ring resonators presented in different articles.

Recently, channel drop filters based on 2D photonic crystals withs quare and triangular lattices have attracted much attention. In this regard,several kinds of CDF based on 2D photonic crystal ring resonator have been presented by using quasi-square PCRR [30], square PCRR [30], dual square PCRR [30], dual curved PCRR [24], hexagonal PCRR [31], 45◦ PCRR [32], circular PCRR [33], X shaped ring resonator [34], elliptical rings [35], H-shape photonic crystal ring resonators [31]. In this paper, we have proposed and designed a new configuration for the ring resonator inspiring the ring designs reported in [28], [29], [34].

The most popular plane wave expansion (PWE) method is used for calculating the band structure with and without defects[34].The performance of filters with triangular lattice of silicon rods in air background are investigated by using two-dimensional finite-diference time-domain numerical method. The present work is carried out by Rsoft - Fullwave and Bandsolve software which is used to simulate and study of the electromagnetic waves behaviour in the proposed structure.

The rest of the paper is arranged as follows: Section 2 presents a brief review of numerical method which is used in our simulations. In Section 3 we describe the ring resonator structure and CDFs. Simulation results are discussed in Section 4 . The design goal is to obtain a wavelength selective device able to drop central wavelength. Section 5 presents a multiplexer using of PCRR designed in this paper. Section6 concludes the paper.

2. METHODS OF NUMERICAL ANALYSIS

The design and simulation play a very important role in the development of the optical devices. With suitable simulation tools, the design of optical devices becomes much more efficient. By using efficient designs that provide good performance and compactness, the cost for product development could be reduced dramatically.Extract and analyze the properties of PC devices, one needs to employ some numerical methods. Plane wave expansion method and the finite-difference time-domain method are most popular methods which is used for theoretical analysis of photonic crystal structures at frequency domain [33]. To study structures with photonic crystals, we make use of the Finite Difference Time Domain method (FDTD).

The FDTD method is a rigorous solution to Maxwell’s equations and does not have any approximations or theoretical restrictions. FDTD method could be used for complex structures which BPM can’t cope with or is not adequate enough. Since the first algorithm, written by Yee in 1966 [34], FDTD method has emerged as a primary means to computationally model many scientific and engineering problems dealing with electromagnetic wave interactions with material structures.

For a region of space where there is no flowing currents or isolated charges, we can rewrite Eq(1), (2) as:

$$\frac{\partial H}{\partial t} = \frac{1}{\mu(r)} \nabla \times E \qquad (1)$$

$$\frac{\partial E}{\partial t} = \frac{1}{\varepsilon(r)} \nabla \times H \qquad (2)$$

Where $\mu(r)$ and $\varepsilon(r)$ are the position dependent permeability and permittivity of the material, respectively. In the two-dimensional case, the fields can be decoupled into two transversely polarized modes as the TM and TE. These equations are discretized in space and time domain using the principles of Yee algorithm [34].

The FDTD mesh size and time step are $\Delta X = \Delta Y = \frac{a}{32}$ and $\Delta t = \Delta X / 2c$ (c is speed of light in free space and *a* is lattice constant) respectively. To obtain the time response of the filter, a pulse excitation which consists of a Gaussian envelope functionmultiplying a sinusoidal carrier with 2^{17} time steps is used at the input waveguides which is adequate to excite the fundamental waveguide mode and PC ring resonator evanescent modes. Berenger's perfectly matched layers (PMLs) are surrounded the whole structure as absorbing boundary condition [4]. This structure is excited with TM polarization.

PWE method is most common method which is used for theoretical analysis of photonic crystal structures. This method can express periodic structures as a superposition of a set of plane waves. And it can obtain an accurate solution for the dispersion properties of a PC structure, but due to considering propagation modes, transmission spectra and field distribution cannot be extracted. Dispersion diagrams of our structures are calculated using this method [4].

3. STRUCTURE DESIGN

The proposed ADF is designed using two dimensional triangular lattice PCs. The number of rods considered for both'X' and 'Z' directions are 17. The radius of the rod is 0.2a (a is lattice constant) and the Si rod is embedded in air. The band diagram shown in Fig. 1 depicts the propagation modes and TM (transverse electric) PBG for refractive index 3.46. As we see there are two PBG in TM mode. Only the widest PBG in TM mode is suitable for fiber optic communication window which is between $0.27 \leq a/\lambda \leq 0.44$, where λ denotes the optical wavelength in free space. This wavelength range covers the optical communication range, so our basic structure is suitable for designing the proposed optical filter.

A common way to implement a channel drop filter is to use a ring resonator. In this kind of setup a forward traveling mode of our bus waveguide excites the clockwise mode of the ring resonator. The power will flow continuously in one direction through the ring and can be transferred to the backward travelling mode of the receiver [36].

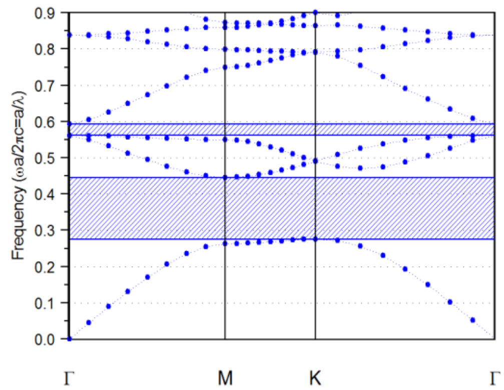


Fig.1. Band structure of triangular lattice photonic crystal of TM polarized light

Fig. 2 shows, the ring resonators' structure designed in this article. Six extra scattering rods with yellow color are introduced to improve the spectral selectivity and obtain a very high dropped efficiency [26]. These scatterers have exactly the same refractive indexes as all other dielectric rods in PC structure and their diameters is chosen to be r_S= 0.965*r for better performance. As shown in Fig. 2, by adding the four extra scatterer rods with blue color at each corner of the ring resonator, which are the same as other rods, the performance of the ring resonator is improved. Back-reflections at the sharp corners of the ring lead to appear undesirable propagating mode[4]. Adding the four extra rods, act like a right-angled reflector, minimizes the effect of these modes.

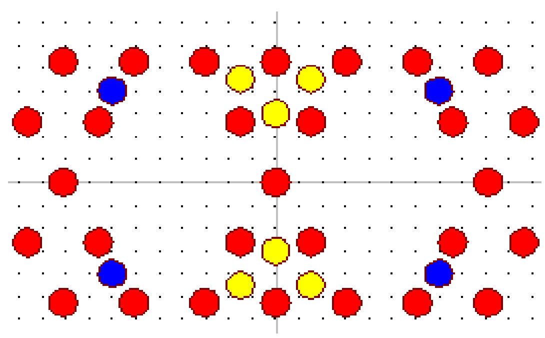


Fig. 2. Schematic structure of PCRR

Optical filters can be used for separating nearly spaced optical channels from each other in WDM applications. 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. The final sketch of the proposed PCRR-based CDF is shown in Fig. 3. It consists of two waveguides (bus and dropping waveguides) and a PCRR between them (coupling element). Similar to any other PCRR-based CDF.

our proposed structure has four ports; input port (A), forward transmission port (B), backward drop port (C) and forward drop port (D). Optical beams enter the structure through port A and exit it from port B, however at the desired wavelength the optical wavelengths drop to other waveguide through the resonant ring and travel toward port D.

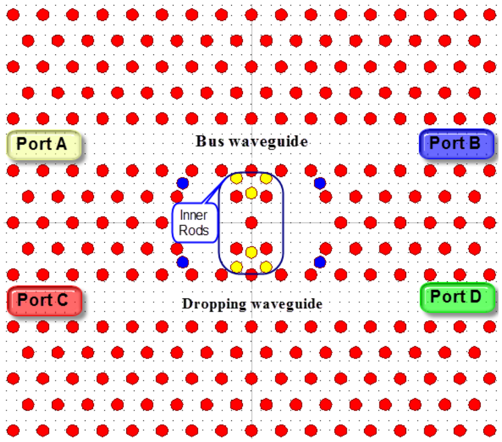


Fig. 3. The schematic diagram of the proposed CDF.

4. SIMULATION RESULTS AND DISCUSSION

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 and output ports.

The normalized transmission spectra at ports B, C and D are displayed in Fig. 4. The normalized transmission of the structure at port B, C and D are depicted with green, red and blue curves. 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. 100% forward dropping efficiency is achieved while the operating wavelength is 1534.5*nm*. *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. The value of *Q* factor for the proposed structure is obtained 153.4. Fig. 5. Electric field pattern of the ring resonator at (a) 1492.3 *nm* (non-resonant wavelength) and (b) 1534.5 *nm* (resonant wavelength).

The significant feature of this structure is that by varying the structure’s parameters, the resonant wavelength can be tuned. In next section, we are going to investigate the effect of varying refractive index of dielectric rods and refractive index of inner rods on the output spectrum of the filter.

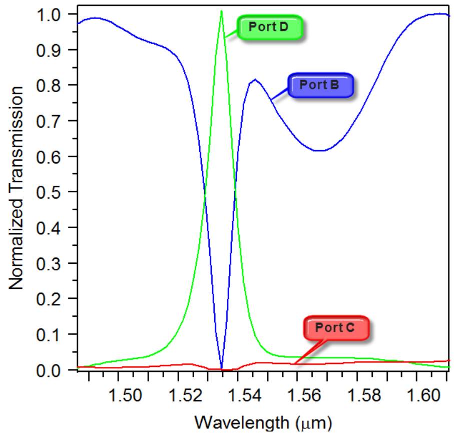
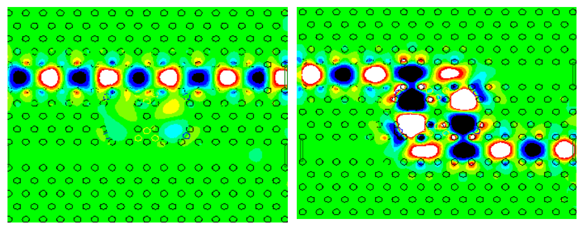


Fig. 4. Transmission spectra of the CDF at ports B, C and D respectively.



(a) (b)

Fig. 5. Electric field pattern of the ring resonator at (a) 1492.3 nm (non-resonant wavelength) and (b) 1534.5 nm (resonant wavelength).

4.1. Effect of Varying Refractive Index

One of the most important features of any filter is its tenability[37]. Here we investigate parameters which affect resonant wavelength in photonic crystal CDFs. The first parameter that we are going to investigate is the refractive index of dielectric rods. In order to separate the effect of refractive index from other parameters, we assume all other parameters such as radius of rods and lattice constant of inner rods to be constant. Then obtain the output spectra of the filter for different values of refractive index. The output spectra of the filter for five different values of refractive index [38] are shown in Fig. 6. In [27,37,38], it is expressed that by increasing the refractive index, they have observed a desired red shift in the output wavelength of the proposed filter that happen in this paper also. Five different curves are displayed in Fig. 6 for *n*=3.4, *n*=3.42,*n*=3.44, *n*=3.46, *n*=3.48 and *n*=3.5. The transmission efficiency of all wavelengths the structure is 100%.

After studying effect of varing of refractive index of structure's dielectric rods we are going to investigate the effect of varing of refractive index of inner rods on the output wavelength of the filter. Another parameter which can influence the operation of proposed filter, is varing of refractive index of inner rods.

The output spectra for different refractive index [39]of inner rods shown in Fig. 7. As shown in Fig. 7, the proposed structure, when simulated with the different refractive index equal to *n*=3.59, *n*=3.69 and *n*=3.79, can select wavelengths 1538.4*nm*, 1542*nm* and 1547.5*nm*, respectively. It can be concluded that refractive index of the inner rods and dielectric rods are suitable parameters for tuning the filter.

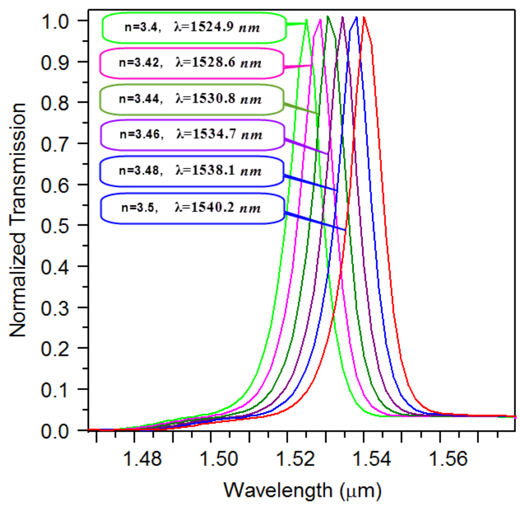


Fig. 6. Transmission spectra of the proposed CDF for different values of refractive index of dielectric rods.

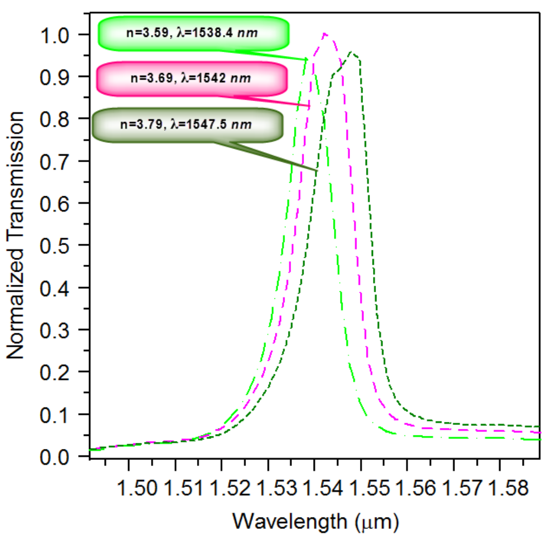


Fig. 7. Transmission spectra of the proposed CDF for different values of refractive index of inner rods.

5. HETEROSTRUCTURE WAVELENGTH DIVISION MULTIPLEXING (WDM)

In the last decade, the high-speed and broad-band optical networks have developed rapidly due to the demand for internet services. Wavelength division multiplexing (WDM) technology provides an efficient way to increase the number of the channels and achieve the demanded bandwidth. 1310/1550 nm WDM systems are frequently used in the fiber-to-the-home applications and asynchronous transfer mode passive optical networks [39]. Wavelength Division Multiplexing (WDM) technology is employed to enhance the single fibre carrying more than one channels with different wavelengths. The WDM techniques are classified as Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM)[40].

This paper is considered to design DWDM demultiplexer and its functional parameters are investigated. The schematic structure is sketched in Fig 8. As shown in this figure, the DWDM is composed of three parts with different refractive index. This DWDM based on new PCRR proposed in this paper.

.

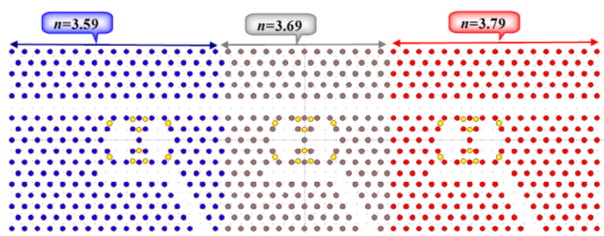


Fig. 8. Schematic structure of DWDM based on 2-D PCRR heterostructure.

Three different curves are displayed in Fig. 9 for 3.59, 3.69 and 3.79. As seen in Fig. 9, the proposed structure, when simulated with the different dielectric constants equal to 3.59, 3.69 and 3.79, can select wavelengths 1553.6 nm, 1573.3 nm, and 1581.4 nm, respectively.

As shown in Fig. 9, by raising the dielectric constant, the resonant wavelength of the device is increased accordingly.

We confirmed by numerical calculations that the variation in the refractive index of silicon rods leads to a change in the center wavelength of the output channels. On the other words, by modulating the refractive index of silicon rods, the center wavelengths of the dropped signals are tuned. The forward dropping efficiencies are 100% at all output channels and the corresponding wavelengths are 1553.6 nm, λ = 1573.3 nm and λ = 1581.4 nm respectively.

For better understanding the operation of device, the distribution of the optical field within the structure is shown in Fig10.

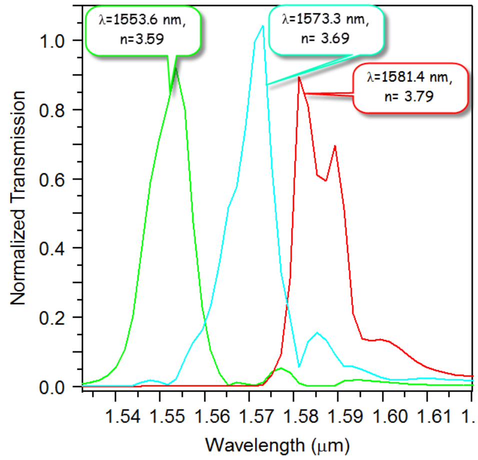


Fig. 9. Normalized power transmission spectra of the proposed structure for DWDM.

(a)

(b)

(c)

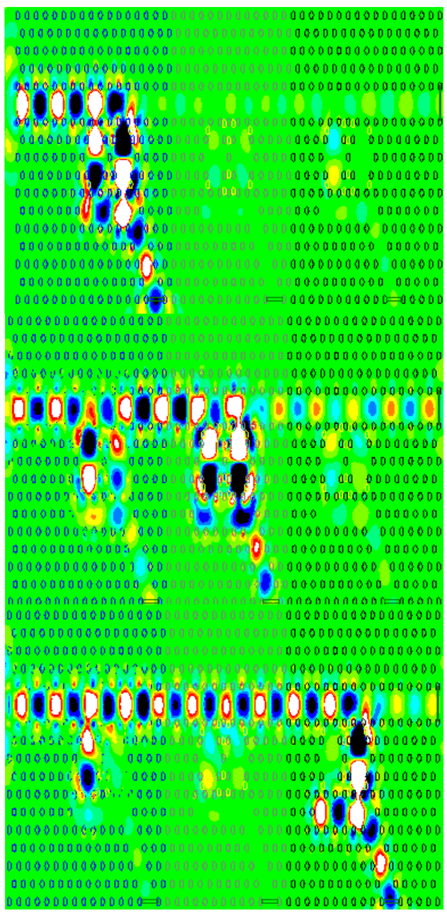


Fig. 10. Electric field patterns of the DWDM at the resonant wavelength (a) λ = 1553.6 nm, (b) λ = 1573.3 nm (b) λ = 1581.4 nm

The electric field patterns at 1553.6 nm, λ = 1573.3 nm and λ = 1581.4 nm are shown in Fig. 10(a)–(c) respectively

6. CONCLUSION

In this paper, a new design for PCRR based on channel drop filter is proposed and numerically demonstrated in two-dimensional triangular lattice silicon rods. The output efficiency and resonant wavelength are examined by varying refractive index of whole rods and the refractive index in inner rods. Dropped efficiency of 100% can be achieved at 1534.5 *nm*. It is observed that increase in refractive index of the structure results in shifting the center wavelength to the higher wavelength. Therefore, varying the refractive index of inner rods and dielectric rods are suitable parameters for tuning the filter. Features of the proposed CDF are new configuration for the ring resonator,small size, high efficiency, suitable quality factor ,densely,tuning and easily fabrication and integration. The overall dimension of the device is only about 10.32μm×10.32μm, which makes it suitable for photonic integrated circuits. Also, Based on the proposed device, a DWDM based on 2-D PCRR hetero structure obtained. The present device could be used in future CWDM communication systems.

REFERENCES

[1] H. Alipour-Banaei, F. Mehdizadeh, M. Hassangholizadeh-Kashtiban, **"A new proposal for PCRR-based channel drop filter using elliptical rings,"** *Physica E 56* , pp. 211–215, 2014.

[2] S. Robinson, R. Nakkeeran, **"Single and dual PCRR in square lattice for filtering applications,"** *Energy Procedia 14*, pp. 1343–1348, 2012,.

[3] H. Alipour-Banaeia, S. Serajmohammadib, F. Mehdizadehc, **"All optical NOR and NAND gate based on nonlinear photonic crystal ring resonators,"** *Optik.125*, pp. 5701–5704, 2014.

[4] M. Djavid, M.S. Abrishamian, **"Multi-channel drop filters using photonic crystal ring resonators,"** *Optik. 123*, pp. 167– 170, 2012.

[5] S. Robinson, R. Nakkeeran, **"Investigation on two dimensional photonic crystal resonant cavity based bandpass filter,"** *Optik 123*, pp. 451– 457, 2012.

[6] H. Alipour-Banaei, F. Mehdizade ,M. Hassangholizadeh Kashtiban, **"A Novel Proposal For All Optical Phc-Based De multiplexers Suitable For DWDM Applications,"** *Journal of Optical and Quantum Electronics*, Vol. 45, No. 10, pp. 1063-1075, 2013.

[7] G. Manzacca, D. Paciotti, A. Marchese, M.S. Moreolo, G. Cincotti, **"2D photonic crystal cavity-based WDM multiplexer,"** *Photon. Nanostruct.: Fundam. Appl. 5*, pp. 164–170, 2007.

[8] A. Ghaffari, F. Monifi, M. Djavid, M.S. Abrishamian, **"Heterostructure wavelength division demultiplexers using photonic crystal ring resonators,"** *Opt. Commun. 281*, 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," *Opt. Lett. 32*, 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 Photon. Technol. Lett. 21*, 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 Opt. 121*, pp. 684–688, 2010.

[12] M.K. Moghaddam, A.R. Attari, M.M. Mirsalehi, **"Improved photonic crystal directional coupler with short length**," P*hoton. Nanostruct.: Fundam. Appl. 8*, pp. 47–53, 2010.

[13] F. Monifi, M. Djavid, A. Ghaffari, M.S. Abrishamian, **"A new bandstop filter based on photonic crystals,"** *Proc. PIER I*, pp. 674–677, 2008.

[14] R. Costa, A. Melloni, M. Martinelli, **"Bandpass resonant filters in photonic-crystal waveguides**," *IEEE Photon. Technol. Lett*. 15 (3), pp. 401–403, 2003.

[15] J. Barvestani, **"Omnidirectional narrow bandpass filters based on one-dimensional superconductor–dielectric photonic crystal heterostructors,"** *Physica B 457*, pp. 218–224, 2015.

[16] C.C. Wang, L. W. Chen, **"Channel drop filters with folded directional couplers in two-dimensional photonic crystals,"** *Physica B 405*, pp. 1210–1215, 2010.

[17] S. Robinson, R. Nakkeeran, **"Channel drop filter based on 2D square-lattice photonic crystal ring resonator**," *in: 7th IEEE International Conference on WOCN'10*, Sri Lanka, September 6–8,1–4, 2010.

[18] J.J. Vegas Olmos, M. Tokushima, K. Kitayama, **"Photonic add–drop filter based on integrated photonic crystal structures,"** *J. Sel. Top. Quantum Electron. 16*, pp. 332–337, 2010.

[19] B.S. Darki, N. Granpayesh, **"Improving the performance of a photonic crystal ring- resonator-based channel drop filter using particle swarm optimization method,"** *Opt. Commun. 283*, pp. 4099–4103, 2010.

[20] P. Andalib, N. Granpayeh, **"Optical add/drop filter based on dual curved photonic crystal resonator,"** *in: 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 40*, pp. 3151–3154, 2008.

[22] H. Rena, J. Zhanga, Y. Qina, J. Li, S. Guoa, W. Hub, Ch.Jiangb, Y. Jin, **"Photonic crystal higher order three-port channel drop filter,"** *Optik 124*, pp. 1787– 1791, 2013.

[23] K. Goodarzi, A. Mir, **"Design and analysis of an all-optical Demultiplexer based on photonic crystals**," *Infrared Physics & Technology 68*, pp. 193–196, 2015.

[24] Y. Kanamori, K. Takahashi, and K. Hane, **"An ultrasmall wavelengthselective channel drop switch using a nanomechanical photonic crystal nanocavity**," *Appl. Phys. Lett.,* Vol. 95, No. 17, pp. 171911-1–171911-3, 2009.

[25] Z. Xu, J. Wang, Q. He, L. Cao, P. Su, G. Jin, **"Optical filter based on contra-directionalwaveguide coupling in a 2D photonic crystal with square lattice of dielectricrods,"** *Opt. Express 13*, pp. 5608–5613, 2005.

[26] H. Alipour-Banaei, M. Hassangholizadeh-Kashtiban, F. Mehdizadeh, **"WDM and DWDM optical filter based on 2D photonic crystal Thue–Morse structure**," *Optik 124,* pp. 4416– 4420, 2013.

[27] S. Rezaee, M.Zavvari, **"A novel optical filter based on H-shape photonic crystal ring resonators**," *Optik 126*, pp. 2535–2538, 2015.

[28] Z. Qiang, W. Zhou, R.A. Soref, **"Optical add-drop filters based on photonic crystal ring resonators**," *Opt. Express 15*, pp. 1823–1831, 2007.

[29] T.T. Mai, F.L. Hsiao, C. Lee, W. Xiang, C.C. Chen, W.K. Choi, **"Optimization and comparison of photonic crystal resonators for silicon microcantilever sensors,"** *Sensors Actuat. A: Phys. 165*, pp. 16–25, 2011.

[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*, pp. 0203–0206, 2010.

[31] S. Robinson, R. Nakkeeran, **"Photonic crystal ring resonator based add-drop filter using hexagonal rods for CWDM systems,"** *Optoelectron. Lett. 7* , pp. 0164–0166, 2011.

[32] M. Y. Mahmoud, Gh. Bassou, A. Taalbi and Z. M. Chekroun, **"Optical channel drop filters based on photonic crystal ring resonators**," *Optics Communications .285*, pp. 368–372, 2012.

[33] V. Dinesh Kumar, T. Srinivas, A. Selvarajan, **"Investigation of ring resonators in photonic crystal circuits,"** *Photonics and Nanostructures–Fundamentals and Applications 2,* pp. 199–206, 2004.

[34] Yee, K.S., **"Numerical solution of initial boundary value problems involving Maxwell's equations**." *IEEE Trans Antennas Propag. 14(3)*, pp. 302–307, 1966.

[35] M. Youcef Mahmoud, G. Bassou, F. Metehri, **"Channel drop filter using photonic crystal ring resonators for CWDM communication systems,"** *Optik 125*, pp. 4718–4721, 2014.

[36] M.Y. Mahmoud, G. Bassou, A. Taalbi, **"A new add-drop filter based on two dimen-sional photonic crystal ring resonator,"** *Optik 124*, pp. 2864–2867, 2013.

[37] M. R. Rakhshani, M. A. Mansouri-Birjandi, **"Realization of tunable optical filter by photonic crystal ring resonators**," *Optik 124, pp.* 5377– 5380, 2013.

[38] H. AlipourBanaei, F. Mehdizadeh, M. Hassangholizadeh-Kashtiban, **"T-shaped channel drop filter based on photonic crystalringresonator**," *Optik125, pp.* 4718–4721, 2014

[39] H. Pezeshki, V. Ahmadi, **"Nanoscale effects on multichannel add/drop filter based on 2-D photonic crystal ring-resonator heterostructure,"**

Journal of Theoretical and Applied Physics 2012.

[40] 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.