Islamic Azad University

**Journal of**
**Optoelectronical Nanostructures**

Summer 2018 / Vol. 3, No. 3

# Novel Design for Photonic Crystal Ring Resonators Based Optical Channel Drop Filter

**Zohreh Rashki [*, 1], Seyyed Javad Seyyed Mahdavi Chabok[1]**
[1]Department of Electrical Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran.

(Received 21 Jun. 2018; Revised 17 Jul. 2018; Accepted 20 Aug. 2018; Published 15 Sep. 2018)

**Abstract:** Photonic crystal ring resonators (PCRRs) are traditional structures for designing optical channel drop filters. In this paper, Photonic crystal channel drop filter (CDFs) with a new configuration of ring resonator is presented. The structure is made of a square lattice of silicon rods with the refractive index $n_{si}$=3. 4 which are perforated in air with refractive index $n_{air}$=1. Calculations of band structure and propagation of electromagnetic field through devices are done by plane wave expansion (PWE) and finite difference time domain (FDTD) methods, respectively. The simulation shows, 100% dropping efficiency and suitable quality factor at 1592. 6 *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 proposed structure is small which is more suitable for used in the future photonic integrated circuits, wavelength division multiplexing (WDM) systems and optical communication network applications. Also, we suggested a heterostructure wavelength demultiplexer is composed of four ring resonators. These ring resonators are located in four different regions (heterostructure) which each region has specific dielectric constant.

**Keywords: Photonic Crystal, Ring Resonators, Square Lattice, Photonic Integrated Circuits, Optical Communication.**

## 1. INTRODUCTION

Optical communication is one of the greatest successes researchers achieved in the last century. In recent decades, optical filters for optical communication networks have received enormous attention. Optical filters are one of the fundamental building blocks for optical communication systems and Wavelength Division Multiplexing (WDM) and Dense Wavelength Division Multiplexing (DWDM) [1]. The channel drop filter (CDF) is one of the most significant devices for CWDM systems to add and/or drop a required channel

[*] Corresponding author. Email: **zohrehrashki@mshdiau.ac.ir**

individually from multiplexed output channels without disturbing other channels [2–5]. In the other words, by employing optical filters one can separate the very closely spaced optical channels without using any electronic devices [6–8]. Due to ever increasing developments in optical communication networks, Designing ultra small devices which are suitable for integrated all optical circuits always is very interesting for optics and photonics researchers. Generally, planar lightwave circuits (PLC), microelectro mechanical systems (MEMS), and photonic crystals (PhCs) are providing a fascinating platform for a new generation of integrated optical devices and components of ultra-compact sizes in the cm to μm range[7]. Developing ultra-small optical components for photonic integrated circuits (PICs) is currently the subject of intense research. One crucial challenge in designing ultra-compact optical devices is the poor confinement of light in small spaces. This challenge has been solved through employing photonic crystals [4].

In recent years, photonic crystal structures have received enormous attention to be used in optical telecommunication systems and integrated circuits in nano size. PhCs are periodic optical nanostructures composed of two different materials with low and high dielectric constant [5, 6]. As a result of this periodicity, it possesses photonic band gap (PBG). PBG is a wavelength range in the band structure of photonic crystals which the propagation of any electromagnetic wave is forbidden. 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. 1D PhCs which is also called multilayer do not have a complete PBG and also fabrication of 3D PhCs is very difficult due to their very small lattice constant. 2DPhCs have refractive index changes in two perpendicular directions that play an important role in designing photonic devices due to ease in controlling their propagation modes, accurate calculation of PBG, efficient light confinement, simple design, and easy fabrication capability[7, 8]. Easiest fabrication of devices and complete Photonic Band Gapgeneration is one of the most important factors to select 2DPhC lattice in the present work. The 2DPhC lattice structures are classified in to triangular lattice and square lattice. The triangular lattice is composed of air pores in dielectric slab and square lattice is composed of periodic array of dielectric rods in air medium. The square lattice has low dielectric strength compared to triangular lattice, hence, square lattice is mostly proposed to design PhC based devices.

Compared with conventional optical devices, PhC-based optical devices have attracted great interest due to their compactness (10 to 100 times) compared to conventional devices, high speed of operation, better confinement, suitability for integration [9].

By introducing some defects (point and/or line and/or both) in these structures, the periodicity and thus the completeness of the band gap are disturbed and the propagation of light can be localized in the PBG region[9, 10]. This can lead to design a PhC based optical devices in the PBG region. In recent years many PhC based optical devices, theoretically and experimentally have been shown possible. These devices include, multiplexers[8-10], channel drop and add-drop filters[11-33], optical switch[34], optical NAND and NOR gates [5], polarization splitters[35] based on PhCs are being researched and fabricated for practical application. .

Optical filtering elements are among the most important components of the telecommunication systems. Filters are classified according to their frequency domain properties. Customary filters are low-pass, high-pass, band-pass, band-stop, all-pass and notch filters [36, 37, 38]. In recent years, various constructions have been proposed for performing filtering behavior based on PhC structures. Defect structures, resonant cavities coupled waveguides and ring resonators are some examples of proposed filtering mechanisms [28-32]. Photonic crystal ring resonators (PCRRs) are common structures for designing optical channel drop filters. PCRRs also can be used for realizing optical switches, optical sensors, optical demultiplexer, etc. The first report of a photonic-crystal ring resonator (PCRR) proposed by Kumar et al [39] Djavid et al [40] proposed a T-shaped channel drop filter based on PCRRs. Mahmoud et al. [12, 13] proposed another channel drop filter based on X-shaped ring resonator structure. Elliptical rings [16] and H-shape photonic crystal ring resonators[41] another ring resonator structure proposed by H. Alipour-Banaei et al, S. Rezaee et al, respectively.

In this paper, a new configuration of PCRR based on CDF is proposed and numerically demonstrated in square lattice photonic crystal silicon rods using the two-dimensional (2D) finite-difference time-domain (FDTD) technique. The new ring resonator introduced in this study can be used as the basic element for other devices.

We investigate parameters which have an effect on resonant wavelength and transmission spectrum in this CDF, such as refractive index of inner and whole rods of the structure. Also, In this paper, we design a heterostructure wavelength demultiplexer based on ring resonators.

The remainder of the paper is organized as follows: Section 2 presents a brief review of numerical method which is used in our simulations. In Section 3 we analyze structure design. we describe the ring resonator structure and analyze channel drop filters in Section 4. The design goal is to obtain a wavelength selective device able to drop central wavelength. Section 5 describes the design of the heterostructure demultiplexer using ring resonators and shows the simulations results, and finally in Section 6 we conclude the proposed work.

## 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 PhC devices, one needs to employ some numerical methods. Plane wave expansion (PWE) 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 [36]. PWE method is used for theoretical analysis of photonic crystal structures and develop PBG in PhC and estimate the wavelength range with the support Maxwell's equations. The fundamental solutions are described as follows [42].

$$\nabla \times E + \frac{\partial B}{\partial t} = 0 \tag{1}$$

$$\nabla \bullet B = 0 \tag{2}$$

$$\nabla \times H - \frac{\partial D}{\partial t} = J \tag{3}$$

$$\nabla \bullet D = \rho \tag{4}$$

The Maxwell's electromagnetism as an eigen value problem for the harmonic modes of the magnetic field H(r) equation is

$$\nabla \times \left( \frac{1}{\varepsilon(r)} \nabla \times H(r) \right) = \left( \frac{\omega}{c} \right)^2 H(r) \tag{5}$$

The solution of electric field is

$$\nabla \times \nabla \times E(r) = \left( \frac{\omega}{c} \right)^2 \varepsilon(r) E(r) \tag{6}$$

The above said solutions are used to solve an eigen value problem.

FDTD method is employed to analysis the performance of electric field distribution among 2DPhC and accord the transmission spectra of PhC based Optical devices. Since the first algorithm, written by Yee in 1966 [43], FDTD method has emerged as a primary means to computationally model many scientific and engineering problems dealing with electromagnetic wave interactions with material structures. The Maxwell's equations help to perform Finite Difference Time Domain simulation of electromagnetic devices for all WDM ranges of frequencies. It is an efficient method to utilize the basic Maxwell's equations are[42]. .

$$E_X\Big|_{i,j}^{n+1} = E_X\Big|_{i,j}^{n} + \frac{c\Delta t}{\varepsilon_0}\left[\frac{H_Z\big|_{i,j+1/2}^{n+1/2} - H_Z\big|_{i,j-1/2}^{n+1/2}}{\Delta y}\right] \tag{7}$$

$$E_y\Big|_{i,j}^{n+1} = E_y\Big|_{i,j}^{n} - \frac{c\Delta t}{\varepsilon_0}\left[\frac{H_Z\big|_{i+1/2,j}^{n+1/2} - H_Z\big|_{i-1/2,j}^{n+1/2}}{\Delta x}\right] \tag{8}$$

$$H_Z\Big|_{i,j}^{n+1/2} = E_X\Big|_{i,j}^{n-1/2} + \frac{c\Delta t}{\varepsilon_0}\left[\frac{\left[Ex\big|_{i,j+1/2}^{n} - E_x\big|_{i,j-1/2}^{n}\right]}{\Delta y}\right] - \left[\frac{\left[E_y\big|_{i+1/2,j}^{n} - E_y\big|_{i+1/2,j}^{n}\right]}{\Delta x}\right] \tag{9}$$

The FDTD mesh size and time step are $\Delta X = \Delta Y = a/32$ and $\Delta t = \Delta X / 2c$ . Here, 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 function multiplying a sinusoidal carrier with $2^{17}$ time steps is used at the input waveguides which is adequate to excite the fundamental waveguide mode and PhC ring resonator evanescent modes.

## 3. STRUCTURE DESIGN

The design in this paper is based on two-dimensional (2D) square lattice of silicon rods with refractive index $n_{Si}$=3. 4 in an air background with $n_{air}$=1. 00. Also the number of rods in the plate x-z is equal to 21×21. In this investigation, the ratio of the rod radius r to the lattice constant a, is 0. 17. Which is a lattice constant (the distance between the centers of two adjacent rods). 2D PWE methods are employed to estimate the square 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 $0.37 \leq a/\lambda \leq 0.53$ for TM polarization, where $\lambda$ is the wavelength in free space. This wavelength range covers the optical communication range, so our basic structure is suitable for designing the proposed optical filter.

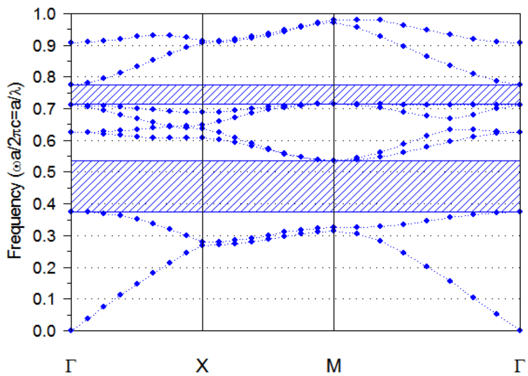


**Fig 1**. Band diagram of PhC square lattice structure.

### *3.1 Optical Ring Resonator-Based on CDFs*

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 and numerous design parameters [22]. These parameters can be the radius of the scaterers, coupling rods and the dielectric constant of the structure. Recently, several types of CDF based on 2D PCRR have been proposed using PCRR [6]. The ring resonators presented in this study is a new configuration 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. twelve extra scattering rods with yellow color are introduced to improve the spectral selectivity and obtain a very high dropped efficiency [6]. These scatterers have exactly the same refractive indexes as all other dielectric rods in PhC structure and their diameters is chosen to be $r_s=1.3r$ for better performance.

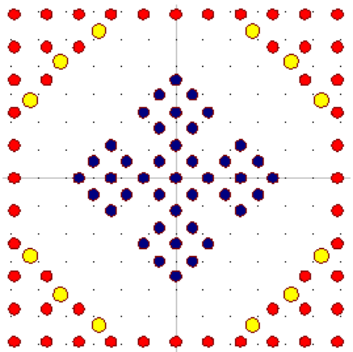

**Fig 2.** Demonstration of the designed PCRR.

## 4. Filter design and Simulation results

Optical filters are one of the most important building blocks of optical communication networks which play a crucial role in wavelength division multiplexing technologies. The channel drop filter (CDF) is one of the most significant devices for coarse wavelength division multiplexing systems to add and/ or drop a required channel individually from multiplexed output channels without disturbing other channels. The important parameters of the CDF are coupling efficiency, dropping efficiency and *Q* factor. In general, a ring resonator is positioned between two optical waveguides provides an ideal basic structure for CDF that power in one waveguide is transferred into the other through the resonance of the ring. 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 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 CDF responses are simulated using the 2D-FDTD method [27].

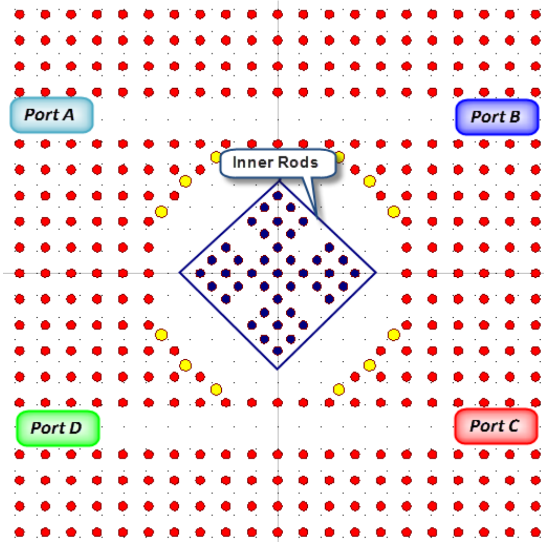


**Fig 3.** The schematic diagram of CDF

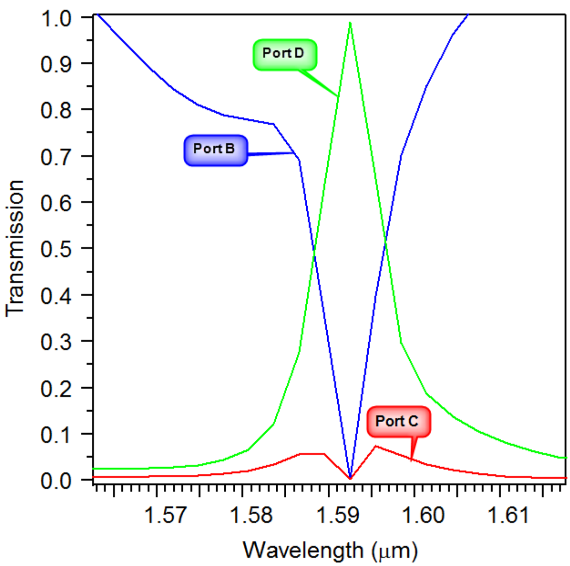


**Fig. 4**. Optical power transmission spectrum of our proposed CDF

The transmission spectra at ports B, C and D are displayed in Fig. 4. At resonance, the filter's main output is Port D. The filter's desired wavelength performance is the conventional L- band and U-band (1. 575~1. 675μm) of optical telecommunications. Also, 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 1592. 6 *nm*. Fig. 5 (a) and (b) shows the electric field distributions of the structure proposed in Fig. 5 for two different wavelengths, $\lambda 1$ = 1553. 5 nm and $\lambda 2$ = 1592. 6 nm. The value of *Q* for the proposed structure is obtained 228. 57. *Q* factor can be calculated with $Q = \lambda/\Delta\lambda$, where $\lambda$ and $\Delta\lambda$ are central wavelength and full width at half power of output, respectively. We note that the amount of 228. 57 is a suitable quality factor for ring resonator based filter. Table 1 compares the results of the proposed design with other PCRR-based filter. To our knowledge it is first time that a resonance region with diamond -shape design is presented.

**Table 1.** Comparison of designed PCRR filter with the existed PCRR-based filter

| **Authors/Year** | Dropping effi-ciency (%) | Quality factor | Type of PCRR |
|---|---|---|---|
| Present work | 100 | 228. 57 | Diamond shaped |
| Chhip et al /2016[46] | 99 | 192 | Curved Fabry–Perot |
| Rezaee et al/2015[41] | 100 | 221 | H-shape |
| Mahmoud et al/2013[12] | 100 | 196 | X shaped |
| Robinson et al/2011[44] | 100 | 128 | Circular shaped |
| Andalib et al/2008 [45] | 68 | 153. 6 | Dual curve shaped |

The significant feature of this CDF is that by varying the structure parameters, the resonant wavelength can be tuned. In next sections, we are going to investigate the effect of different parameters on the output spectrum of the filter.

Section 4. 1 describes the effect of varying refractive index of rods, Section 4. 2 describes the effect of varying refractive index of inner rods.

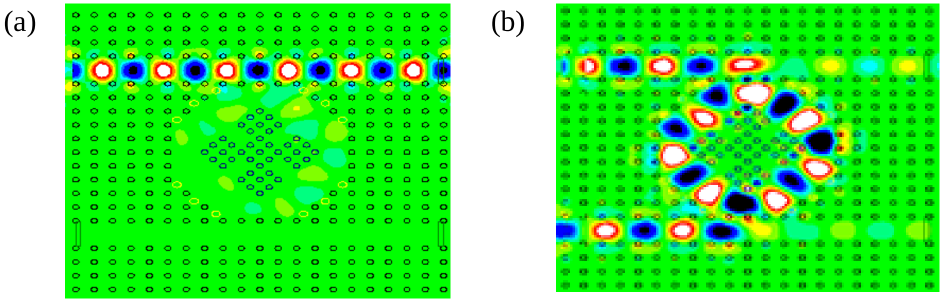


**Fig. 5.** Electric field pattern of the ring resonator at (a) 1553. 5 *nm* (non-resonant wavelength) and (b) 1592. 6 *nm* (resonant wavelength).

### 4.1 VARYING THE REFRACTIVE INDEX OF RODS

One of the most important features of any filter is its tenability. Here we investigate parameters which affect resonant wavelength in photonic crystal CDFs. First parameter 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 different values of refractive index [34] are shown in Fig. 6. In [16, 21, 28], 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. Six 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.

### 4.2 VARYING OF INNER RODS REFRACTIVE INDEX

After studying effect of fundamental structure we are going to investigate the effect of varying of inner rods refractive index on the output wavelength of the filter. With localized change in inner rods' refractive index, the resonant wavelength can be tuned. This leads to a tunable CDF. the output spectra for different refractive index [36]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 1604. 4nm, 1610. 9nm and 1613. 7nm, respectively.

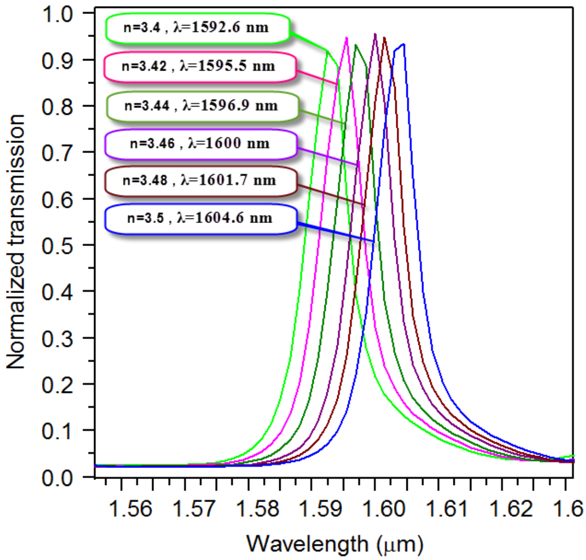


**Fig. 6.** The output spectra of the proposed filter for different values of refractive index.

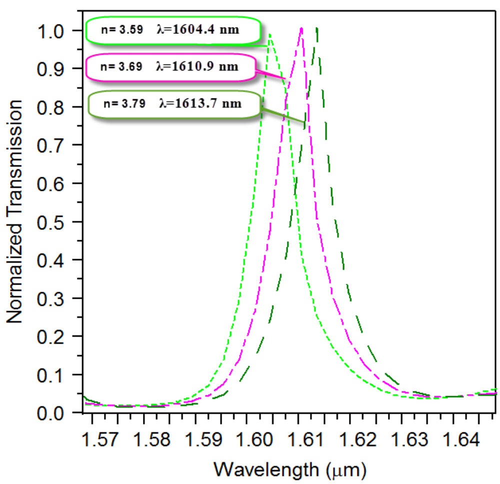


**Fig. 7.** Transmission spectra of the proposed CDF for different values of refractive index of inner rods.

## 5. HETEROSTRUCTURE WAVELENGTH DEMULTIPLEXER

In this section, we present a design of heterostructure PhC wavelength demultiplexer using ring resonators with four outputs. This wavelength demultiplexer contains four regions with various dielectric constants as shown in Fig. 8. In order to achieve the structure of demultiplexer, four improved rings with different dielectric constants of 3.49, 3.59, 3.69, and 3.79 [36] have been used. Every ring has an individual dielectric constant; it means that each ring has a variable resonant wavelength. These different refractive indexes can produce with electro-optic (E-O) or thermo-optic (T-O) materials. Refractive indexes of E-O materials are changed in response to the external electric field [26]. In T-O materials we can control the refractive index through the heat generated by optically produced carriers.

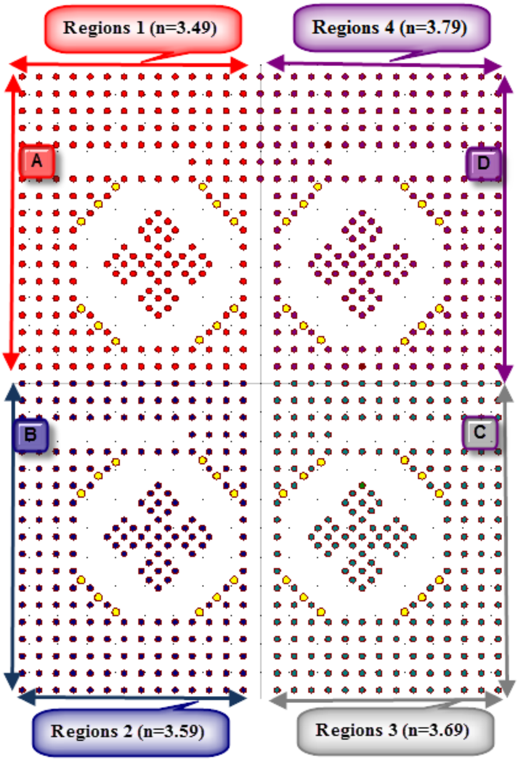


**Fig. 8.** Schematic of Heterostructure wavelength demultiplexer.

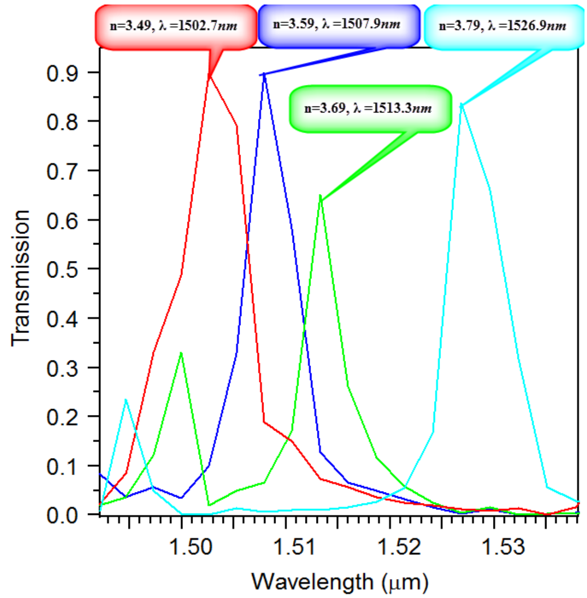


**Fig. 9.** Optical power transmission characteristic of our proposed demultiplexer structure for output ports A, B, C, and D.

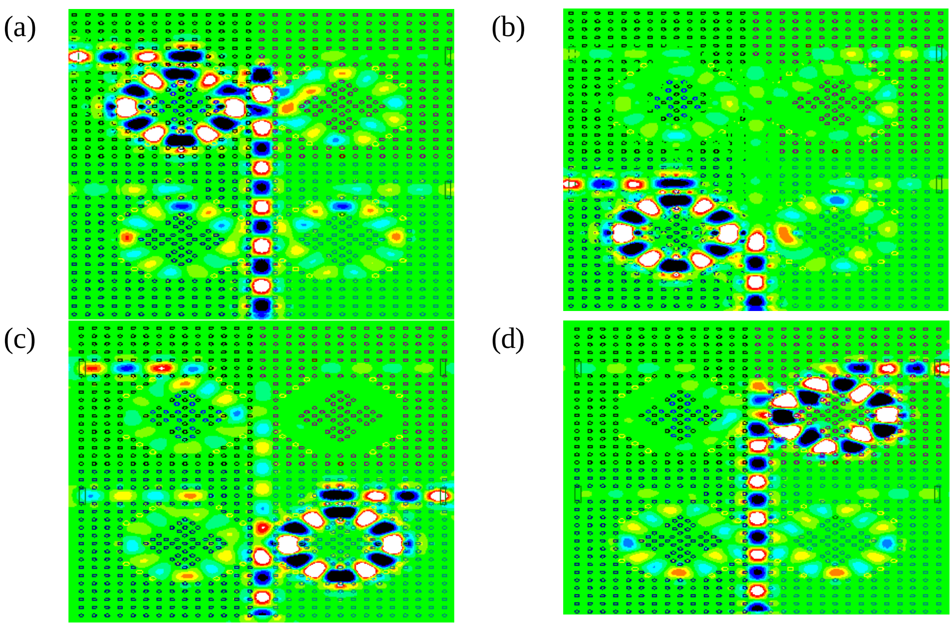


**Fig. 10.** Field distributions of our proposed demultiplexer structure for (a) n= 3. 49, $\lambda_1$=1502. 8nm, (b) n= 3. 59, λ2=1508nm, (c) n= 3. 69, λ3=1513. 4nm, and(d) n= 3. 79, λ4=1526. 8nm.

This structure is named a heterostructure PhC, because it is created from four sub-structures with different refractive index. In order to prevent propagation losses at the boundary of the different dielectric constant substructures, the band gap of these substructures must be overlapped in some range of frequency. We explore four structures bandgaps using a two dimensional plane wave expansion method for TM polarization. The structures of regions 1, regions 2, regions 3 and 4 have following band-gaps: $0.36 \le a/\lambda \le 0.52$, $0.35 \le a/\lambda \le 0.51$, $0.34 \le a/\lambda \le 0.50$ and $0.33 \le a/\lambda \le 0.49$, 3 respectively. Certainly, four different regions have individual band gaps. These four band gaps must be overlapped in some ranges of frequencies. Which its range depends on the parameters namely *r/a* and dielectric constant [4]. This means that equivalent band-gap of the heterostructure channel drop filter is overlapping of the band-gap of its constitutive structures. Since different PhCs have different band gap ranges, an equivalent band gap of the heterostructure demultiplexer is the overlapping band gaps of substructures [47]. According to the band-gaps of four regions the equivalent band-gap is equal to: $0.35 \le a/\lambda \le 0.49$, In this equivalent band-gap, incident wave can be transmitted through the waveguide, crossed two regions, without any reflection and losses. Four ports of the structure are labeled as A, B, C, and D, shown in Fig. 8. In this structure, we have four ring resonators which one of them is put in four region. The resonant wavelength of the four channel demultiplexer for regions 1, regions 2, regions 3 and 4 are 1502.8 *nm*, 1508 *nm*, 1513.4 *nm*, and 1526.8 *nm*, respectively. Fig. 9 shows the normalized transmission of this heterostructure wavelength demultiplexer. The outputs efficiencies are over 90%, 90%, 65% and 83% at the resonant wavelength: 1502.8 *nm*, 1508 *nm*, 1513.4 *nm*, and 1526.8 *nm*, respectively. As seen in Fig. 9, the structure is successful in separating the different incident wavelengths to different outputs. Fig. 10 shows FDTD simulated results of the steady state field distributions of wavelength demultiplexer with ring resonators at (a) $\lambda 1$=1502.8 *nm* of port A, (b) $\lambda 2$=1508 *nm* of port B, (c) $\lambda 3$=1513.4 *nm* of port C, and (d) $\lambda 4$=1526.8 nm of port D in the third communication window.

## 6. CONCLUSIONS

In this paper, a new design for PCRR based on channel drop filter is proposed and numerically demonstrated in two-dimensional square 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 1592. 6 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, high efficiency, suitable quality factor, densely, tuning and easily fabrication and integration.

The overall dimension of the device is only about 12. 36μm×12. 36μm, which makes it suitable for photonic integrated circuits. Also, a novel device scheme for a heterostructure 4-channel wavelength demultiplexer with completely PhCs rings had been introduced and investigated through FDTD method.

## REFERENCES


[1] E. Ozbay, K. Guven, E. Cubukcu, K. Aydin, Alici *Negative refraction and subwavelength focusing using photonic crystals*. Modern Physics Letters B, 18(25) (2004, October, )1275–1291.
Available: https://doi. org/10. 1142/S0217984904007803.

[2] Joannopoulos J. D, Johnson S. G, Winn J N, Meade R D. *Photonic Crystals: Molding the Flow of Light*. Princeton: Princeton University Press, 2011.

[3] E. Najafi Tomraei, H. Rasooli Saghai, *All-optical photonic crystal filters in the form of series hexagonal rings for application in advanced optical communication systems*, Optik, 136 (2017, May) 84–88.
Available: https://doi. org/10. 1016/j. ijleo. 2017. 02. 011

[4] M. Djavid, M. S. Abrishamian, *Multi-channeldrop filters using photonic crystal ring resonators*, Optik, 123 (2012, January) 167–170.
Available: https://doi. org/10. 1016/j. ijleo. 2011. 04. 001

[5] H. Alipour Banaeia, S. Seraj mohammadib, F. Mehdizadehc, *All optical NOR and NAND gate based on nonlinear photonic crystal ring resonators*, Optik, 125 (2014, October)5701–5704.
Available https://doi. org/10. 1016/j. ijleo. 2014. 06. 013:

[6] E. Yablonovitch. *Inhibited spontaneous emission in solid-state physics and electronics.* Phys. Rev. Lett. 58, (1987)2059–2062

[7] H. Alipour-Banaei, F. Mehdizadeh, M. Hassangholizadeh-Kashtiban, *T-shaped channel drop filter based on photonic crystal ring resonator*, Optik, 125 (2014, September) 4718–4721.
Available: https://doi. org/10. 1016/j. ijleo. 2014. 06. 056

[8] H. Alipour-Banaei, F. Mehdizadeh, S. Serajmohammadi. *A novel 4- channel demultiplexer based on photonic crystal ring resonators*. Optik-International Journal for Light and Electron Optics, 124(23)(2013, December)5964–5967.
Available: https://doi. org/10. 1016/j. ijleo. 2013. 04. 117

[9] H. Alipour-Banaei, F. Mehdizadeh, *Significant role of photonic crystal resonant cavities in WDM and DWDM communication tunable filters*. Optik, 124(2013, September) 2639–2644.
Available: https://doi. org/10. 1016/j. ijleo. 2012. 07. 029

[10] A. Rostami, H. Alipour Banei, F. Nazari, A. Bahrami, *An ultra-compact photonic crystal wavelength division demultiplexer using resonance cavities in a modified Y-branch structure.* Optik 122(2011, August) 1481–1485.

Available: https://doi. org/10. 1016/j. ijleo. 2010. 05. 036

[11] S. Robinson, R. Nakkeeran, *Two dimensional photonic crystal ring resonator based add-drop filter using hexagonal rods for CWDM systems*. Optik, 124(2013, September) 3430–3435.
Available: https://doi. org/10. 1016/j. ijleo. 2012. 10. 038

[12] M. Y. Mahmoud, G. Bassou, A. Taalbi, Z. M. Chekroun, *Optical channel drop filter based on photonic crystal ring resonators*. Opt. Commun. 285(2013, February) 368–372.
Available: https://doi. org/10. 1016/j. optcom. 2011. 09. 068

[13] M. Y. Mahmoud, G. Bassou, A. Taalbi, *A new optical add-drop filter based on photonic crystal ring resonators*. Optik, 124(2013, September) 2864–2867.
Available: https://doi. org/10. 1016/j. ijleo. 2012. 08. 072

[14] M. Y. Mahmoud, G. Bassou, F. Metehri, *Channel drop filter using photonic crystal ring resonators for CWDM communication systems*. Optik, 125(2014, September) 4718–4721.
Available: https://doi. org/10. 1016/j. ijleo. 2014. 04. 084

[15] V. Fallahi1, M. Seifouri, *Design of an Improved Optical Filter Based on Dual-Curved PCRR for WDM Systems*, Journal of Optoelectronical Nanostructures, Vol. 2, No. 3 ( 2017, )45-56.
Available: http://jopn. miau. ac. ir/article_2573. html

[16] H. Alipour-Banaei, F. Mehdizadeh, M. Hassangholizadeh-Kashtiban, *A new proposal for PCRR-based channel drop filter using elliptical rings*. Phys. E 56 (2014, February)211–215.
Available: https://doi. org/10. 1016/j. physe. 2013. 07. 018

[17] E. Rafiee, F. Emami, *Design and Analysis of a Novel Hexagonal Shaped Channel Drop Filter Based on Two-Dimensional Photonic Crystals*, Journal of Optoelectronical Nanostructures, Vol. 1, No. 2 (2016)39-46.
Available: http://jopn. miau. ac. ir/article_2047. html

[18] A. Dideban, H. Habibiyan, H. Ghafoorifard, *Photonic crystal channel drop filter based on ring-shaped defects for DWDM systems*. Phys. E Low Dimens. Syst. Nanostruct. (2017, March) 77-83.
Available: https://doi. org/10. 1016/j. physe. 2016. 11. 022

[19] S. Li, H. Liu, Q. Sun, N. Huang, *Multi-channel terahertz wavelength division demultiplexer with defects-coupled photonic crystal waveguide*. J. Mod. Opt 63(2016, November) 955-960.
Available: https://doi. org/10. 1080/09500340. 2015. 1111457

[20] Y. Lu, H. Liu, Q. Sun, N. Huang, Z. Wang, *Terahertz narrowband filter based on rectangle photonic crystal*. J. Mod. Opt 63(2016, November) 224-228.
Available: https://doi. org/10. 1080/09500340. 2015. 1111457

[21] M. R. Rakhshani, M. A. Mansouri-Birjandi, Z. Rashki, *Design of six channel de-multiplexer by hetero structure photonic crystal resonant cavity*, Int. Res. J. Appl. BasicSci. 4(4)(2014)976–984.
Available: www. irjabs. com/files_site/paperlist/r_781_130422111503. pdf

[22] S. Robinson, R. Nakkeeran, *Investigation on two dimensional photonic crystal resonant cavity based bandpass filter*, Optik 123 (2012, March) 451–457.
Available: https://doi. org/10. 1016/j. ijleo. 2011. 05. 004

[23] F. Mehdizadeh, H. Alipour-Banaei, S. Serajmohammadi, *Channel-drop filter based on a photonic crystal ring resonator*. J. Opt 15, (2013, May) 075401.
Available: https://doi. org/10. 1088/2040-8978/15/7/075401

[24] L. Li, G. Q. Liu, *Photonic crystal ring resonator channel drop filter*. Opt. Int. J. Light Electron Opt. 124(17)(2013)2913–2915.
Available: https://doi. org/10. 1016/j. ijleo. 2012. 09. 012

[25] Y. Zheng, S. Li, and J. Kang, *Two dimensional photonic crystal channel filter based on ring resonator,* in IEEE Conf. on Photonics and Optoelectronics, Wahun, China(2009, September) 1–3.
Available: DOI: 10. 1109/SOPO. 2009. 5230214

[26] M. R. Rakhshani, M. A. Mansouri-Birjandi, *Tunable channel drop filter using hexagonal photonic crystal ring resonators*. Telkomnika 11, (2013, January) 513-516.
Available: DOI: 10. 11591/telkomnika. v11i1. 1788

[27] Z. Rashki, M. A. Mansouri Birjandi, *New design of optical add-drop filter based on triangular lattice photonic crystal ring resonator*, Tech. J. Eng. Appl. Sci. 3, (2013) 441-445.
Available:www. irjabs. com/files_site/paperlist/r_782_130422111653. pdf

[28] S. Robinson. R. Nakkeeran, *Single and dual PCRR in square lattice for filtering applications*, Energy Procedia 14, ( 2012, ) 1343–1348.
Available: https://doi. org/10. 1016/j. egypro. 2011. 12. 1099

[29] A. Taalbi, G. Bassou, M. Y. Mahmoud, *New design of channel drop filters based on photonic crystal ring resonators*. Opt. Int. J. Light Electron Opt124, (2014, May).
Available: https://doi. org/10. 1016/j. ijleo. 2012. 01. 045

[30] Z. Rashki, S. J. SeyyedMahdavi Chabok, *Novel design of optical channel drop filters based on two-dimensional photonic crystal ring resonators*. Opt. Commun. 395, (2017, July) 231-235.
Available: https://doi. org/10. 1016/j. optcom. 2016. 08. 077

[31] A. Dideban, H. Habibiyan, H. Ghafoorifard, *Photonic crystal channel drop filters based on fractal structures. Phys. E LowDimens*. Syst. Nanostruct. 63, (2014, September) 304-306.
Available: https://doi. org/10. 1016/j. physe. 2014. 06. 009

[32] A. Rostami, A. Haddadpour, F. Nazari, H. Alipour. *Proposal for an ultracompact tunable wavelength-division-multiplexing optical filter based on quasi-2D photonic crystals*. J. Opt 12 (2009, November) 015405.
Available: http://dx. doi. org/10. 1088/2040-8978/12/1/015405

[33] Z. Ma and K. Ogusu, *Channel drop filters using photonic crystal Fabry–Perot resonators,* Opt. Commun. 284(5) (2011, March) 1192–1196.
Available: https://doi. org/10. 1016/j. optcom. 2010. 10. 050

[34] T. Ahmadi-Tame, B. M. Isfahani, N. Granpayeh, A. M. Javan, *Improving the performance of all optical switching based onnonlinear photonic crystal micro ring resonator.* Int. J. Electron. Commun. (AEU) 65(2011, April) 281–287.
Available: https://doi. org/10. 1016/j. aeue. 2010. 03. 013

[35] T. Liu, A. R. Zakharian, M. Fallahi, J. V. Moloney, M. Mansuripur, *Design of a compact photonic-crystal-based polarizing beam splitter*. IEEE Photonics Technol. Lett. 17, (2005, July) 1435-1441.
Available: DOI: 10. 1109/LPT. 2005. 848278

[36] J. Barvestani, *Omnidirectional narrow bandpass filters based on one-dimensional superconductor–dielectric photonic crystal heterostructors*, Physica B 457 (2015, January) 218–224.
Available: https://doi. org/10. 1016/j. physb. 2014. 10. 019

[37] F. Monifi, M. Djavid, A. Ghaffari, M. Abrishamian, *A new bandstop filter based on photonic crystals*, In: Proceedings of the PIER, Cambridge, USA, (2008, July) 674-677.
Available: https://www. researchgate. net/publication/266228117

[38] W. Suh, S. Fan, *All-pass transmission or flattop reflection filters using a single photonic crystal slab*, Appl. Phys. Lett. 84(24) (2004, May) 4905–4907.
Available: https://doi. org/10. 1063/1. 1763221

[39] V. Dinesh Kumar, T. Srinivas, A. Selvarajan, *Investigation of ring resonators in photonic crystal circuits*, Photonics and Nanostructures – Fundamentals and Applications 2 ( 2004, December)199–206.
Available: https://doi. org/10. 1016/j. photonics. 2004. 11. 001

[40] M. David, A. Ghaffari, F. Monifi, M. S. Abrishamian, *T-Shaped channel drop filters using photonic crystal ring resonators*, Physica E 40, (2008, September) 3151–3154.
Available: https://doi. org/10. 1016/j. physe. 2008. 05. 002

[41] S. Rezaee, M. Zavvari, *A novel optical filter based on H-shape photonic crystalring resonators*, Optik - International Journal for Light and Electron Optics (2015, October) 2535-2538.
Available: https://doi. org/10. 1016/j. ijleo. 2015. 06. 043

[42] K. Venkatachalam D. Sriram Kumar S. Robinson, *Performance analysis of 2D-Photonic Crystal based Eight Channel Wavelength Division Demultiplexer,* Optik(127)(2016, October) 8819-8826.

Available: https://doi. org/10. 1016/j. ijleo. 2016. 06. 112

[43] K. S. Yee, *Numerical solution of initial boundary value problems involving Maxwell's equations*. IEEE Trans Antennas Propag. 14(3), (1966, May) 302–307. Available: DOI:10. 1109/TAP. 1966. 1138693

[44] S. Robinson, R. Nakkeeran, *PCRR based add drop filters using photonic crystal ring resonators*, Optic-Int. J. Light Electron Optik (2012, June). Available: DOI: 10. 1117/1. OE. 52. 6. 060901

[45] P. Andalib, N. Granpayeh, *Optical add/drop filter based on dual curved photonic crystal resonator*. In: IEEE/LEOS International Conference on Optical MEMS and Nanophotonics (2008, August). Available: DOI: 10. 1109/OMEMS. 2008. 4607883

[46] M. K. Chhipa, M. Radhouene, A. Dikshit, S. Robinson, B. Suthar, *Novel compact optical channel drop filter for CWDM optical network applications*. Int. J. Photonics Opt. Technol. 2 (4), (2016, December)26–29. Available: http://www. ijpot. org/papers/pdf/1478941371-2410. pdf

[47] M. Djavid, M. S. Abrishamian, *Multi-channel drop filters using photonic crystal ring resonators*, Optik 123 (2012, January) 167– 170. Available: https://doi. org/10. 1016/j. ijleo. 2011. 04. 001