Add-Drop and Channel-Drop Optical Filters Based on Photonic Crystal Ring Resonators

Alireza Tavousi, Mohammad Ali Mansouri-Birjandi, and Mehdi Saffari

Abstract—**Here, we propose an add-drop and a channel drop filter based on two-dimensional photonic crystal all circular ring resonators. These structures are made of a square lattice of silicon rods with the refractive index n_1=3.464 surrounded by air (with refractive index n_2=1). The broadest photonic band gap occurs at the filling ratio of r/a = 0.17. Two linear defect W1 waveguides couple to the ring. Our add-drop and channel drop filters form by the appropriate coupling distance between the ring and waveguide. The dropping efficiency of both filters in their operational window - the C (1.535-1.565µm) and L (1.565-1.625µm) bands of optical telecommunications - is almost %100 and corresponds to a deca-pole degenerated resonant mode. Normalized frequencies (a/λ), in degenerated mode equal to 0.3684 and 0.3645. Resonant modes of the all circular ring resonator with their corresponding degenerated poles and the transmission spectra are calculated using the PWE, and 2D-FDTD methods respectively.**

Index Terms—*add-drop filter; channel drop filter; photonic crystal; ring resonator.*

I. Introduction

PHOTONIC CRYSTALS (PCS) are multidimensional periodic structures composed of low and high index semiconductor materials arranged respectively. They are designed to affect the motion of light and prohibit the propagation of electromagnetic waves in all directions within predefined wavelength ranges known as photonic band gaps (PBGs) [1].

The simplest form of a PC is a one-dimensional thin film stack, where thickness of the two different materials is in the order of a quarter of wavelength. Since the concept of a thin-film stack has already existed for more than a century, it was only much later that the idea of PCs with two or three dimensions appeared [2, 3].

When a point or line defect is introduced within these structures, their periodicity breaks and the light confines within their PBG. Using this property, several kinds of optical devices can be constructed based on PCs [4, 5].

Optical devices based on PCs, have received many interests in scientific communities for their high speed, high capacity, high performance, long life and compactness which makes them suitable for integration purposes. In recent years many optical devices are made based on PCs such as multiplexers [6], de-multiplexers [7], polarization beam splitters [8], and add-drop filters [9], channel-drop filters [10-12] and so on.

Optical filters are able to selectively transmit light in a specified wavelength window, while the remainders are blocked. One can design filters so they pass signals in some frequency bands, and attenuate them in others. It is customary to classify filters according to their frequency domain characteristics. In the following we can name a few, i.e, low-pass, high-pass, band-pass, band-stop, all-pass and notch filters.

The wavelength selective filter is one of the attractive devices fabricated based on PCs. These types of filters are very important for optical telecommunication systems. Although yet the greatest focus on the PC based wavelength selective filters, has been on the add-drop filters [9], we will focus on other filters such band-pass, band-stop, channel drop filters too.

Ring resonators are fascinating elements for dense wavelength division multiplexing (DWDM) and photonics integrated circuits (PICs). Photonic crystal ring resonators (PCRR) can be considered as a new type of linear defects which their size is determined by the desired resonant wavelength. In comparison with point or linear defect, for reasons such as scalability in size and having many design parameters such as scattering rods radius, the distance between rods and the refractive index of the structure, PCRRs offer better flexibility and adaptability in the structure design [8]. The advantage of PCRRs over conventional integrated optical devices is their functionality and their compactness. These are two important key attributes using PCRRs as building blocks for large scale integration [3-5, 9].

This work develops two compact integrated optical filters by the mean of PCRRs, *add-drop* and *channel-drop* filter. The novelty of this research consists in the designing of all circular PCRR to meet DWDM filtering needs with high dropping

Manuscript received May 30, 2012.

Alireza Tavousi is a MSc. Student at the Electronics Department, Chabahar Campus, University of Sistan and Baluchestan, Zahedan, Iran (e-mail: ali_r_tavoosi@yahoo.com).

Mohammad Ali Mansouri Birjandi is with the Faculty of Electrical and Computer Engineering, University of Sistan and Baluchestan, Zahedan, Iran (corresponding author to provide phone: +98-541-805-6549; e-mail: mansouri@ece.usb.ac.ir).

Mehdi Saffari is with the Faculty of Electrical and Computer Engineering, University of Sistan and Baluchestan, Zahedan, Iran (e-mail: m.saffari@ece.usb.ac.ir).

efficiency, high coupling efficiency and tenability [9].

Since the optical properties and construction technology of optical integrated device based on silicon is well known, and also Si material provides a wide PBG for its large refractive index difference with air [2, 3, and 13], it is selected as the first choice material used in the present paper.

The desired wavelength performance window is located within the C (1.53~1.565μm) and L (1.565~1.625μm) bands of optical telecommunications used in DWDM [4, 14].

Filters Simulations have been done using Finite Difference Time Domain (FDTD) numerical method and the PBG has been calculated by plane wave expansion (PWE) method.

In order to develop an efficient and reliable FDTD simulation in the modeling process, we used Beranger's perfectly matched layer (PML) absorbing boundary conditions (ABC) which is based upon splitting the H and E field components in the ABC area and assigning artificial electric and magnetic loss coefficients. Beranger's PML ABC is considered to be the best material ABC currently available because of its excellent absorption over a wide range of angles and its insensitivity to frequency [15, 16].

This paper's organization is as follow: in the second part of the paper, we discuss the design procedures of different wavelength selective filters. We discuss about the simulation results in Section III and in the last section, we express the conclusions.

II. STRUCTURE DESIGN

A. *Design and Optimization of PC's Perfect Lattice*

The system under consideration is an array of rods with a two-dimensional square lattice. The refractive index of silicon rods is n_1=3.464 and the environment is air with refractive index n_2=1. The number of rods in the x-z plane is 17 × 19.

To find the best rod's radii for which the PBG is maximum in the TE polarization, we draw the gap map in terms of filling ratio (*r/a*). The best filling ratio that the broadest PBG occurs for it, obtains for r/a = 0.17. The normalized frequency range corresponding to this ratio is $0.3076 \le a/\lambda \le 0.4526$ and the normalized gap width is $\Delta\omega a/2\pi c \approx 0.145$. For the desired wavelength and the chosen rod's radii by considering the center of PBG as a/λ=0.3801 the lattice constant obtains as a= 0.57μm. Also the PBG's corresponding wavelength range is 1.301~1.915μm. The structures overall dimension is calculated about 9μm×10μm.

Figure 1 shows the PC's PBG which is calculated for r/a=0.17 using PWE method with TE (electric field parallel to the rod axis) polarization mode. The 'X' axis represents the line connecting points of first Brillion zone (the smallest periodical space in the lattice structure) and 'Z' axis shows the normalized frequency $\omega a/2\pi c = a/\lambda$ where 'ω' is the angular frequency, 'a' is the lattice constant (distance between centers of two adjacent rods), 'c' is the light speed in the vacuum and 'λ' is the free space wavelength. The existence of PBG for TE mode in the first 2 bands is clearly visible in this figure.

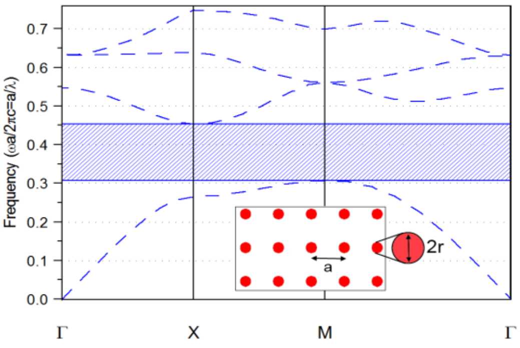


Figure 1. Photonic crystal perfect lattice frequency band structure for TE polarization mode.

B. *Design of Linear Defect Waveguide*

The light is guided toward the PCRR through a W1 waveguide. For depicting the waveguide's dispersion curve, we used a supercell with 7*a*×1*a* dimension and PML boundary condition.

In Fig. 2, the waveguide dispersion curve is depicted. We obtained the waveguide guided mode by collating the dispersion diagrams of the perfect and the deformed lattice (lattice with linear defect W1 waveguide), in the space of irreducible Brillion zone for normalized wave numbers. The beginning of the guided mode (red line) is from the normalized frequency a/λ=0.3142 in the K = Γ symmetry point.

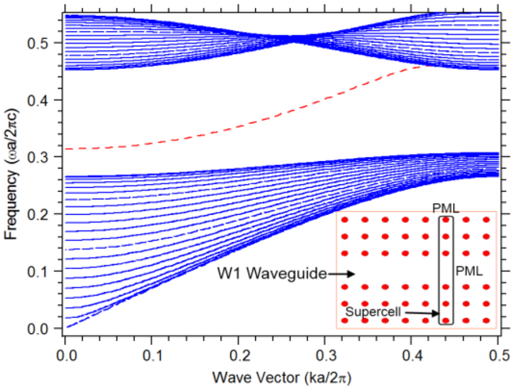


Figure 2. W1 line defect waveguide dispersion curve obtained using PWE method.

C. *PCRRs Design and Optimization*

PCRRs consist of a quasi-circular waveguide in a closed loop side-coupled to one or more bus (or input-output) waveguides. When light with the appropriate wavelength is launched to the input waveguide, it will couple to the ring through evanescent coupling modes and due to constructive interference its intensity builds up in over several round-trips and emits almost whole of it in the drop waveguide. Then it can be grabbed by a pick waveguide. Since only some wavelengths resonate within the ring, it somehow functions as a wavelength selective filter. At resonance, there is also a much higher intensity in the waveguide region. Such intensities are called evanescent as they decay exponentially outside of the waveguide region [4, 7, and 14].

Due to the nature of the PCRRs and how they *filter* certain wavelengths of light passing through, by cascading various PCRRs in series, it is possible to make high-order optical filters. Additionally, by simply increasing or decreasing each ring's radii, the resonance wavelengths can be modified and these filters can be considered tunable [7, 14].

There are many resonant modes for our designed all circular PCRR and they are easily calculated using the PWE method with the condition of an appropriate supercell size. These resonant modes are named as mono-pole, di-pole, quadru-pole, hexa-pole, octa-pole, deca-pole etc. The mono-pole mode often occurs alone, but the others are two degenerate with a phase shift of 180 degree divided by number of poles [12].

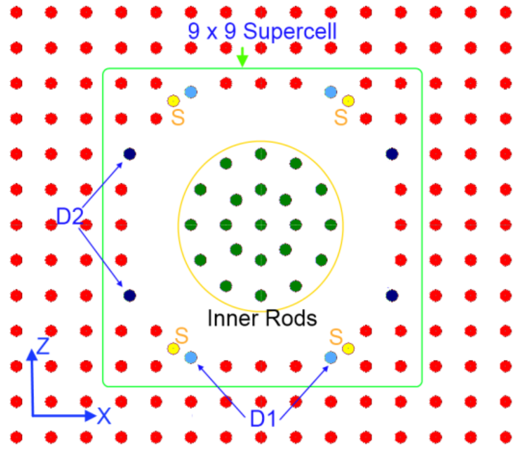


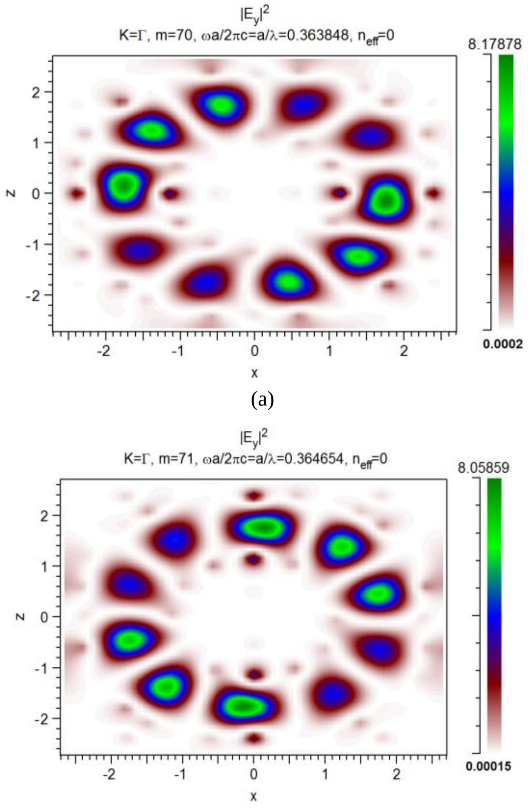
Figure 3. Demonstration of the designed PCRR and its selected supercell which is used to calculate the resonant modes.

Figure 3 shows the PCRR structure that is created by removing a circular row of rods and also shows the supercell used to calculate the resonant modes. The dimensions of these supercell is 9a×9a and the optimum number of bands used to calculate the supercell band structure is 9×(2+9) = 99. Resonant modes calculations carried out using PWE method for the E_y electric field component in the TE polarization mode.

The inner rods are designed perfectly circular to improve the PCRR performance. In addition, four scattering rods which are indicated with label (S) in Fig. 3 and are the same as other rods, have been added in the corners of PCRR, on the center of the imaginary square made by its four adjacent rods. These rods act like wavelength reflectors, so they will decrease back-reflections in the corresponding corners.

To form the circular shape of our PCRR outer rods and to optimize its efficiency, we moved defects labeled as D1 and D2 from their primary places. We have added 8 point-defects to PCRR structure which were optimized through the FDTD method. Also we moved D1 defects (with pale blue) along the 'Z' axis to the %3.5 of their original location and D2 defect (with strong blue) along the 'X' axis to %3.5 of their primary location.

Figure 4 shows the main resonant mode of the proposed all circular PCRR. This mode is a deca-pole with two degenerate states and 18 degree phase shift between them. The modes calculated using PWE method for the $|E_y|^2$ field component for the symmetry point K = Γ in TE polarization mode. Normalized frequencies corresponding to this degenerate deca- pole are a/λ=0.36384 and a/λ =0.36465.



(a)

(b)

Figure 4. The main resonant modes of the all circular PCRR with the normalized frequency (a) 0.363848 and (b) 0.364654, which calculated using PWE method for the $|Ey|^2$ field component and symmetry point K = Γ in the TE polarization mode.

D. Add-Drop Filter

The optical add-drop filter (ADF) is one of the fundamental building blocks for optical modulators, and optical switches needed for PICs, and DWDM optical communication systems [4].

Figure 5 illustrates our designed add-drop filter. This filter has one input and three outputs named as PORT1, PORT2 and PORT3. The bus waveguide is located between the input and PORT1. The dropping waveguide is the other one. The coupling length between the bus waveguide and all circular PCRR, is 3a in the 'X' direction and 1a toward the 'Z' direction. Under Resonance circumstances, the filter's main output is PORT3 which perform the backward-dropping job. The filter's desired wavelength performance is the conventional C- band and L-band of optical telecommunications.

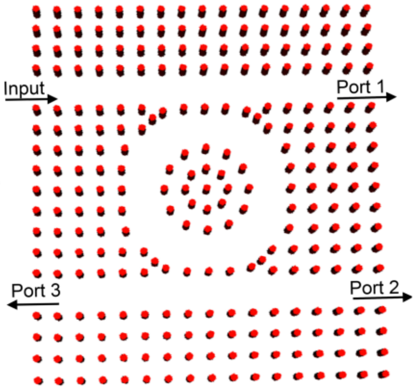


Figure 5. The 3D illustration of designed ADF

E. *Channel-Drop Filter*

By terminating Port 2 of our ADF, another filter named channel-drop filter (CDF) is formed. Figure 6 shows the schematic of our proposed channel drop filter. This filter has one input and two output channels named as PORT1, PORT2.

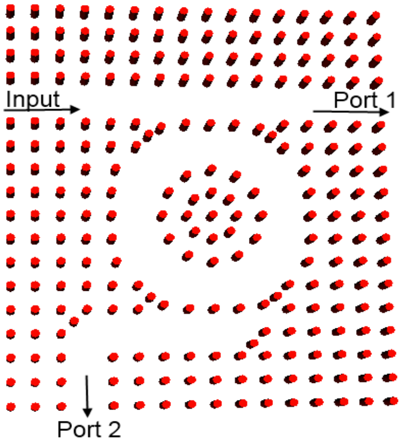


Figure 6. Three-dimensional view of CDF

We have introduced a 60 degrees bend in the drop waveguide. The bend is designed such that its efficiency is 100% which mean there in no attenuation. The coupling length between the bus waveguide and all circular PCRR is the same as ADF. The dropping job in Resonance is performed by PORT2. The filter's desired wavelength performance is the third and forth (C, L bands) telecommunications optical window like ADF.

III. SIMULATION RESULTS

The filters transmission spectra are calculated using the FDTD numerical method with PML ABCs. The FDTD mesh size and time step are $\Delta x=\Delta y= a/64$ and $\Delta t= \Delta x/2c$ (c is speed of light in free space).

To obtain the time response of the filter, a pulse excitation which consists of a Gaussian envelope function multiplying a sinusoidal carrier with 2^{18} time steps is used at the input waveguides which is adequate to excite the fundamental waveguide mode and PCRR's evanescent resonant modes.

Since we desire the frequency (wavelength) response of the filter in order to obtain the spectral characteristics of the structure, we perform a frequency (wavelength) analysis which is based on Discrete Fourier transform (DFT) algorithm on the time response of the filter. Our DFT analysis is calculated for Δλ=1.576µm with center wavelength of λ=1.576µm.

All of the power transmission spectral responses are calculated as the relation of transmitted power versus wavelength and are normalized to the incident light.

A continues wave (CW) Gaussian excitation source is used to simulate the filter's behavior in a single wavelength such on or off-resonance.

A. *Add-Drop Filter*

Figure 7 demonstrates the single ring ADF transmission spectra which are normalized to the incident light. This transmission spectra are depicted for the wavelengths range 1.535~1.625µm which correspond to the C and L-bands.

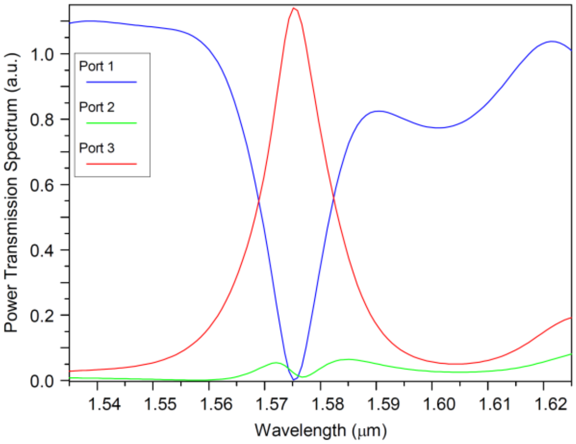
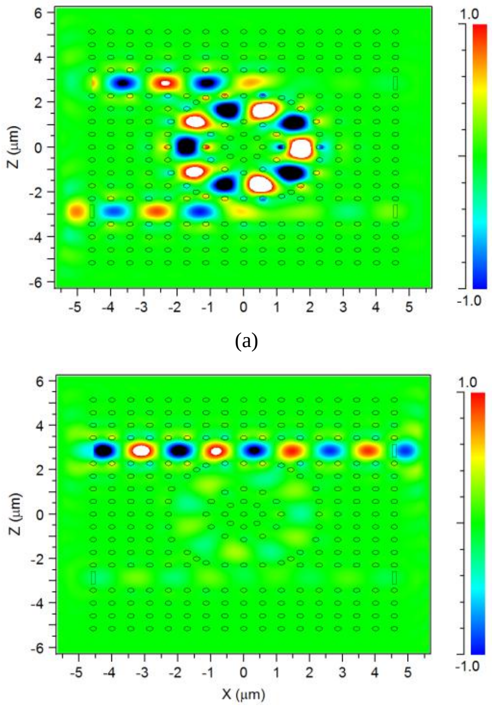


Figure 7. Transmission spectral response of the proposed ADF.

The ADF dropping efficiency for the third output channel is close to %100 at the resonance peak λ=1.576µm. Due to constructive interference there are some ranges of transmission spectra which their intensity builds up in over several round-trips and become more than one.

Figure 8 demonstrates the numerical simulation results for the resonant mode at 1.576µm and non-resonant mode at 1.54µm. As depicted in Fig. 8(a), the best output peak occurs at deca-pole degenerate mode. At resonant wavelength, the electric field of the waveguide is completely coupled to the ring and reaches to output, where at off resonance, i.e. Fig. 8(b) 1.54µm, it doesn't couple with the ring and exit from Port 1.



(a)

(b)

Figure 8. The ADF FDTD numerical simulation results for the degenerate deca-pole resonant mode at (a) 1.576μm (b) 1.54μm.

B. *Channel-Drop Filter*

Figure 9 depicts the single ring CDF normalized transmission spectra for the wavelengths range 1.535~1.625μm which correspond to the C and L-bands.

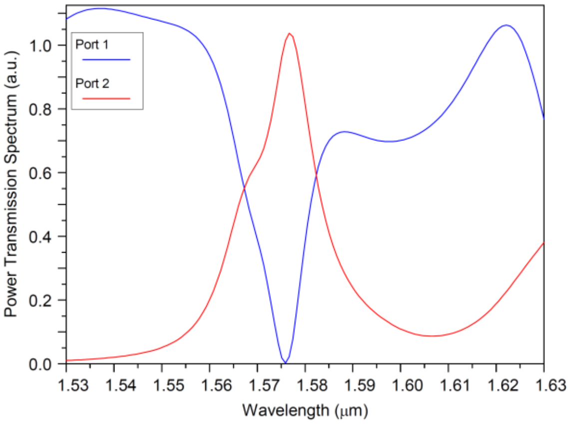
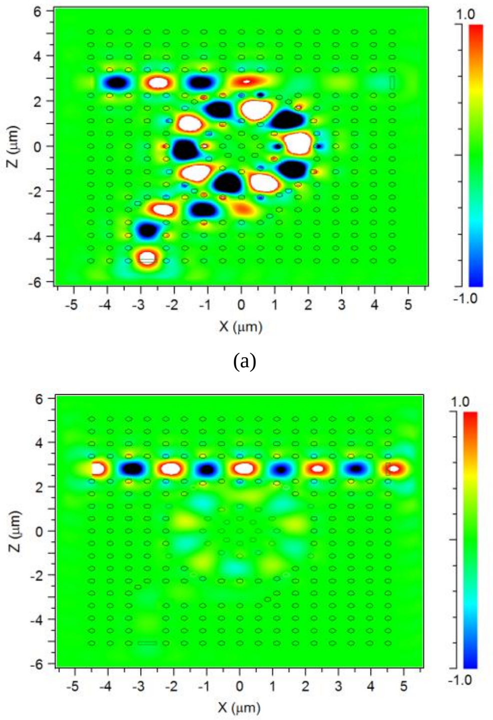


Figure 9. Transmission spectral response of the proposed CDF.

Figure 10 demonstrates the numerical simulation results for the resonant mode at 1.576μm and non-resonant mode at 1.54μm. The best output peak which occurs at deca-pole degenerate mode is depicted in Fig. 10(a).



(a)

(b)

Figure 10. The CDF FDTD numerical simulation results for the degenerate deca-pole resonant mode at (a) 1.576μm (b) 1.54μm.

The CDF dropping efficiency for the second output channel is almost %100 at the resonance peak λ=1.576μm. Similar to ADF the effect of constructive interference on taking the transmission spectra more than on, is obvious. In addition, a Full Width Half Maximum (FWHM) bandwidth of 17nm - from 1.566~1.583μm - is achieved at the output of transmission spectrum.

IV. CONCLUSION

In this study, we proposed an add-drop and a channel drop filter based on two-dimensional photonic crystal all circular ring resonators. These structures were made of a square lattice of silicon rods (with the refractive index n_1=3.464) surrounded by air. The widest PBG happened for the filling ratio of r/a = 0.17. Two linear defect W1 waveguides were instantly clung to the PCRR. With the appropriate coupling distance between the PCRR and waveguide, our add-drop and channel drop filters were formed. The dropping efficiency of both filters in their operational window - C (1.535-1.565μm) and L (1.565-1.625μm) bands of optical telecommunications - was close to %100, and it corresponded to a deca-pole degenerated resonant mode. Normalized frequencies of this degenerate mode were, a/λ = 0.3684 and 0.3645. Resonant modes of the PCRR and their corresponding degenerate poles were calculated using the PWE method; and the transmission spectra were calculated using 2D-FDTD numerical method.

REFERENCES

[1] J. Joannopoulos, S. G. Johnson, N. Winn and R. D. Meade; "*Photonic Crystal: Molding the flow of light*"; Princeton University Press; 2nd Ed. 2008, chap. 1, 2.

[2] K. Inoue and K. Ohtaka; "*Photonic Crystals: Physics, Fabrication and Applications*"; Springer-Verlog, Berlin Heidelburg, pp 274-277, 2004.

[3] M. A. Mansouri-Birjandi, M. K. Moravvej-farshi and A. Rostami; "Ultra-fast low threshold all-optical switch implemented by arrays of ring resonators coupled to a Mach- Zehnder interferometer arm: based on 2D- photonic crystals"; *APPLIED OPTICS*, Vol. 47, pp 5041-5050, 2008.

[4] S. Robinson and R. Nakkeeran; "PCRR based add drop filter for ITU-T G.694.2 CWDM systems"; *OPTIK - INT. J. LIGHT ELECTRON OPT.*, 2012.

[5] M. Djavid and M.S. Abrishamian; "Multi – channel drop filters using photonic crystal ring resonators"; *OPTIK - INT. J. LIGHT ELECTRON OPT.*, 2012.

[6] G. Manzacca, D. Paciotti, A. Marchese, M.S. Moreolo and G. Cincotti; "2D photonic crystal cavity-based WDM multiplexer"; *PHOTON. NANOSTRUCT. FUNDAM. APPL.* Vol. 5, pp. 164–170, 2007.

[7] A. Ghaffari, F. Monifi, M. Djavid and M.S. Abrishamian; "Heterostructure wavelength division demultiplexers using photonic crystal ring resonators"; *OPT. COMMUN.* Vol. 281, pp 4028–4032, 2008.

[8] V. Zabelin, L. A. Dunbar, N. Le Thomas, R. Houdre, M. V. Kotlyar, L. O'Faolain and T.F. Krauss; "Self-collimating photonic crystal polarization beam splitter"; *OPT. LETTERS*, Vol. 32, pp. 530–532, 2007.

[9] Z. Qiang, W. Zhou and R. A. Soref; "Optical add-drop filters based on photonic crystal ring resonators"; *OPT. EXPRESS*, Vol. 15, pp. 1823-1831, 2007.

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

[11] Z. Zhang and M. Qiu; "Compact in-plane channel drop filter design using a single cavity with two degenerate modes in 2D photonic crystal slabs"; *OPT. EXPRESS*, Vol. 12, pp. 2569-2604, 2005.

[12] S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and H. A. Haus; "Channel drop filters in photonic crystals"; *OPT. EXPRESS*, Vol. 3, pp. 4-11, 1998.

[13] M. P. Doss and M. Subadra; "3D Design and Computation Of Ring Resonator With Nano Photonic Crystal Using FDTD Modeling"; *OPTICS: PHENOMENA, MATERIALS, DEVICES, AND CHARACTERIZATION, OPTICS 2011*, India, 2011.

[14] Y. Xiao, B. Min, X. Jiang, C. Dong, and L. Yang; "Coupling Whispering-Gallery-Mode Microcavities With Modal Coupling Mechanism"; *IEEE JOURNAL OF QUANTUM ELECTRONICS*, VOL. 44, NO. 11, NOVEMBER 2008.

[15] F. D. Hastings, J. B. Schneider and S. L. Broschat; "Application of the perfectly matched layer (PML) absorbing boundary condition to elastic wave propagation"; *J. ACOUST. SOC. AM.*, Vol. 100, pp. 3061-3069, 1996.

[16] J. P. Beranger; "A perfectly matched layer for the absorption of electromagnetic waves"; *J. Comp. Phys.*, Vol. 114, pp. 185-200, 1994.

Mohammad Ali Mansouri-Birjandi was born in Birjand, Iran, in 1961. He received the B.S. degree in electronic engineering from University of Sistan and Baluchestan, Zahedan, Iran, in 1986, the M.S. and the Ph.D. degrees in electronics from the Tehran University and Tarbiat Modares University, Tehran, Iran, in 1991 and 2008, respectively.

Currently he is an assistant professor of electronics engineering and since 1992, he is with the Department of electrical and electronics engineering, faculty of electrical and computer, University of Sistan and Baluchestan, Zahedan, Iran. His research areas are photonics, optoelectronics, analog integrated circuits and metamaterials. Also he has served as a reviewer for a number of journals and conferences.

Mehdi Saffari was born in Khash, Iran, in 1961. He received the B.S. degree in electronic engineering from University of Sistan and Baluchestan, Zahedan, Iran, in 1986, the M.S. degree in electronics from the Tehran University, Tehran, Iran, in 1991.

Currently he is a lecturer in the Department of Computer engineering, Faculty of electrical and computer engineering, University of Sistan and Baluchestan, Zahedan, Iran.

Alireza Tavousi was born in Esfahan, Iran, in 1986. He received the B.S. degree in communications engineering from Islamic Azad University of Najafabad Branchnch, Esfahan, Iran, in 2008 and the M.Sc. degree in electronics engineering from University of Sistan and Baluchestan, Zahedan, Iran, in 2012.

Currently he is a PhD student in electronics engineering, Faculty of electrical and computer engineering, University of Tabriz, Tabriz, Iran. His research interests include contribution to the study of photonic band gap structures, photonic crystals and photonic integrated circuits.