Front. Optoelectron. 2016, 9(4): 578–584
DOI 10.1007/s12200-016-0513-7

RESEARCH ARTICLE

All-optical AND/OR/NOT logic gates based on photonic crystal ring resonators

Ashkan PASHAMEHR[1], **Mahdi ZAVVARI** (✉)[1], **Hamed ALIPOUR-BANAEI**[2]

1 Department of Electrical Engineering, Urmia Branch, Islamic Azad University, Urmia, Iran
2 Department of Electrical Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran

Abstract Photonic crystal based ring resonators are best choice for designing all-optical devices. In this paper, we used a basic structure of photonic crystal ring resonators and designed all optical logic gates which are working using the Kerr effect. The proposed gates consisted of upper and lower waveguides coupled through a resonator which was designed for dropping of special wavelength. The resonance wavelength was designed for 1550 nm telecom operation wavelength. We used numerical methods such as plane wave expansion and finite difference time domain (FDTD) for performing our simulations and studied the optical properties of the proposed structures. Our results showed that the critical input power for triggering the gate output was lower compared to previously reported gates.

Keywords photonic crystal (PhC), all optical logic gate, ring resonator, Kerr effect

1 Introduction

At recent years, all optical logic gates have received much interest because of their wide applications in photonic networks, optical communication systems and optical computing systems [1–3]. Since the photonic networks and systems need more bandwidth to route the high speed optical signals, it is inevitable to process the signals in optical domain without any conversion to electronics [4–6]. Hence, development in all optical networks requires high performance all-optical devices. Recently, some groups have reported the realization of all-optical logic gates by using semiconductor optical amplifiers, microring resonators, and photonic crystal (PhC) based devices [7,8]. On the other hand, the refractive index can be modified using electro-optic, thermo-optic or optical Kerr effect. From the mentioned optical phenomena, only Kerr effect can be used for all-optical applications. In materials that possess the Kerr effect, the refractive index can be changed using an optical pump signal which can be subject to design of different light controlled devices [9]. A number of PhC structures have been designed and proposed for all-optical logic gates based on the third-order nonlinear Kerr effect [10,11]. Anadalib et. al. proposed “AND” gate and “NOR” gate designed by PhC nonlinear ring resonators [12,13]. Bai et. al. demonstrated photonic NOT and NOR gates using a single compact PhC ring resonator [14]. However, for previously reported structures, the threshold of input beam should be considerably high to nonlinear effect occur. Since the optical beams in the photonic cross-connections transmit a lossy media, the intensity loss might cause the nonlinear Kerr effect not to occur and consequently the device does not work properly.

In this paper, we proposed a novel type of logic gates which exploit an ‘8’ shape resonator and need a lower threshold input. For such type of logic gate, we studied its functionality and performance operation. We used two-dimensional finite difference time domain (FDTD) numerical method for analysis of light propagation, response in the proposed photonic crystal device. Perfectly matched layers (PMLs) around the simulating regions used for modeling unbounded region to analyze the behavior of the wave, band gaps group velocity and defects modes. We extracted dispersion diagram by plane wave expansion method (PWEM) [15,16]. The paper is organized as follows. In Section 2, the device structure, design principal and operation mechanism of the gates are presented, and the paper is concluded in Section 3.

Received January 16, 2015; accepted December 4, 2015

E-mail: m.zavvari@iaurmia.ac.ir

2 Design of all optical gates based on nonlinear Kerr effect

2.1 Ring resonator

A ring resonator is the main section of a PhC based filter, in which the optical field traveling in adjacent waveguide can be dropped into the resonator and transmitted to the other adjacent waveguide [17–19]. This happens for an identical beam wavelength called resonance wavelength, which is dependent on the shape and structure of resonating section. Ring resonators are obtained by removing a ring shape of dielectric rods in structure lattice [20]. A typical ring resonator is shown in Fig. 1. This structure was proposed for the first time by Taalbi et al. as a filter and provided with 4 ports A, B, C and D [21]. Figure 2 shows the operation of device and according to the figure, the input lights from port A with wavelength of 1550 nm can couple to down waveguide through the ring resonator and pass toward port C, but for wavelengths away from the 1550 nm, the resonance does not occur and the light pass through port B. For our proposed optical gates, we use this type of resonator. The simulations are performed by commercial software RSoft.

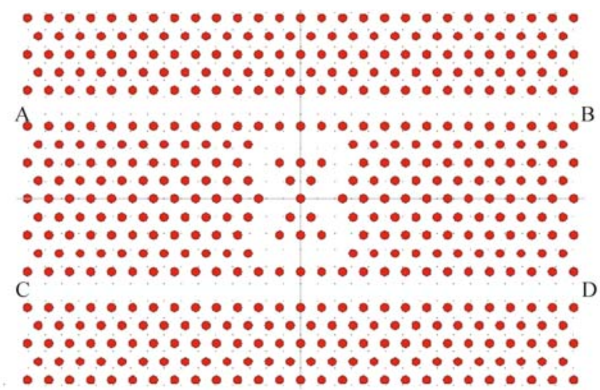

Fig. 1 Typical ring resonator based on photonic crystals

2.2 AND gate

The basic structure used to design an all-optical AND gate is a 30×40 hexagonal array of dielectric rods in substrate of air. The refractive index and the radius of the dielectric rods are considered 3.46 and 124 nm, respectively. Lattice constant is fixed on 616 nm.With these specifications, the basic crystal band structure is calculated and extracted as shown in Fig. 3.

According to the band structure diagram, our basic structure has three forbidden band. Two forbidden bands are created in transverse magnetic (TM) and one in transverse electric (TE). Considering the forbidden bandwidth and crystal lattice constant, first bandgap in TM mode is suitable for our work which is in $0.28 < a/\lambda < 0.44$ range proportional to the wavelength range of $1400\ \text{nm} < \lambda < 2142\ \text{nm}$ that it covers the wavelength range of optical telecommunications. Moreover to better understand the operation of the ring resonator, the transmission spectra of ring resonator in two states are shown in Fig. 4. Figure 4(a) shows that when only A input is on, the peak transmission occurs at $\lambda = 1.55$ μm and the optical field couples to ring and drops to C port. However, if another input is set to high, because of higher order fields in ring resonator, the Kerr effect cause the resonance wavelength to be changed and the transmission reaches near zero. In this case, most of the light passes to the direct B port.

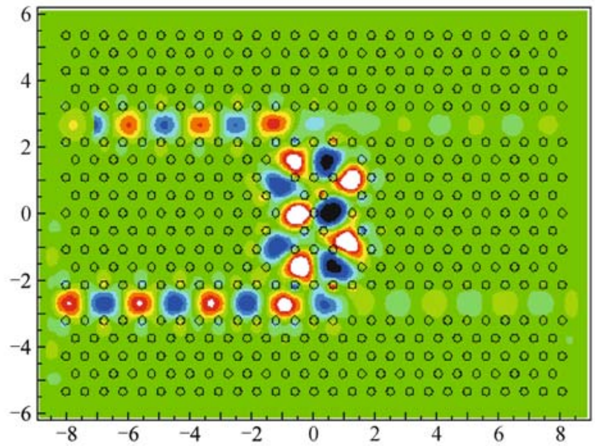

Fig. 2 Field distribution in typical filter based on ring resonator

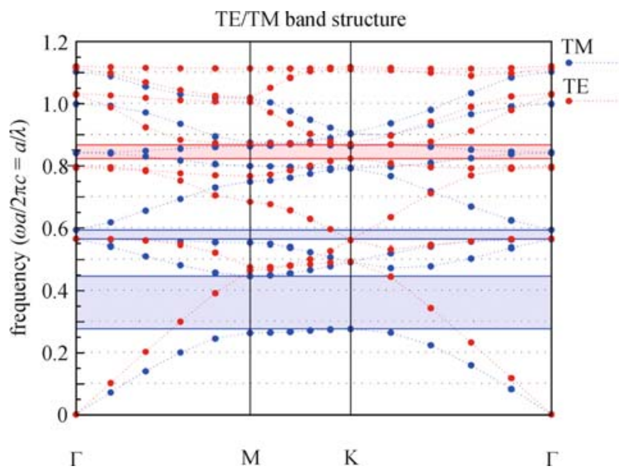

Fig. 3 Band structure diagram for proposed logic AND gate

The proposed AND gate structure is formed from three waveguides and two ring resonators as shown in Fig. 5. The Kerr effect coefficient is considered 1.5×10^{-16} in our calculations.

The structure has three input ports and one output port. Ports — bias, A and B are input ports, out is output port of

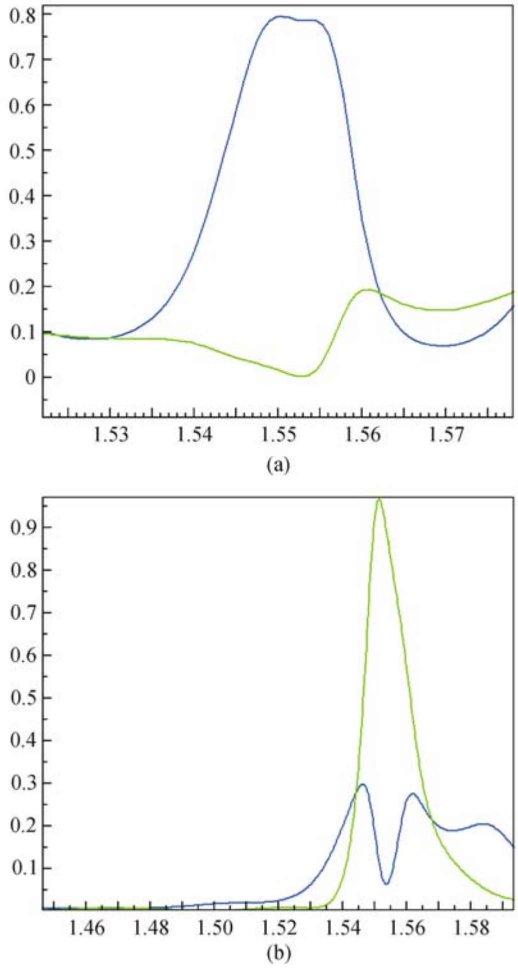

Fig. 4 Transmission spectra for proposed NOT gate when (a) only A input is high; (b) both the A and B inputs are set high. In color figure, the blue curve shows the C port and the green line corresponds to B port

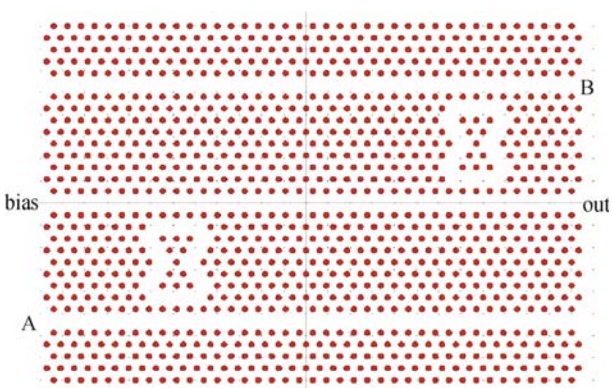

Fig. 5 Proposed AND gate structure formed of three waveguide and two ring resonator

structure. The bias is a continuous wave input and ports A and B are the logic inputs.

The operation of this gate is based on nonlinear effects in the ring resonator. This resonator is such designed that it drops the lights with 1550 nm wavelength from the upper or down waveguides. As we know, the resonant wavelength of the ring resonator is dependent on the refractive index of the ring resonator's core and any variation in the refractive index will change the resonant wavelength. When the high-intensity light enters the ring, the refractive index of rods is changed based on the Kerr effect and therefore it tends to change the resonant wavelength of the ring. Consequently, the bias light cannot be coupled via ring resonator.

The output of proposed AND gate is ON when both of its inputs are turned on and otherwise the output is OFF. For better understanding the operation of AND gate, the optical path of input beams within the structure is sketched in Fig. 6 for different inputs. It is evident from figure that the true table of an AND gate is composed for different terms of inputs. Actually, there are two resonators in the path of bias to the output and the bias beam can couple to each of them to be added to side waveguides and exit through them. On the other hand, each one of the inputs A and B couples to the corresponding resonator and changes its resonant wavelength. To direct the bias beam to the output and have a high state output, the refractive index of both the resonators should be changed and prevent the coupling of bias to them. The details of operation are shown in Fig. 6.

It should be noted that all of this is true when the bias light is in ON state. If the bias port is off, the gate will not be switched on under any conditions. Gate operating modes are provided in Table 1.

2.3 OR gate

The basic structure we use to design an OR all-optical gate is a hexagonal 21×27 array of dielectric rods in air substrate. Refractive index and radius of dielectric rods and lattice constant are 3.46, 24 and 616 nm, respectively. Because the basic structure is similar to the AND gate, so the band diagram is the same. According to the forbidden bandwidth of the crystal and lattice constant, first bandgap of the TM mode is suitable for our applications which is in range of $0.28 < a/\lambda < 0.44$ proportional to the wavelength of $1400\text{ nm} < \lambda < 2142\text{ nm}$.

The proposed OR gate structure is shown in Fig. 7 with two waveguides and one ring resonator.

This structure has three input and one output ports. Ports — bias, A and B are gate's input ports and output port is shown as out in Fig. 7. Ports A and B are named as inputs of the logic gate. The operation principal is similar to the AND gate where the inputs change the resonant wavelength of ring by nonlinear Kerr effect. Once the optical beam enters the ring through at least one of the inputs, the effective refractive index of ring changes and prevent from coupling of the bias beam into the ring.

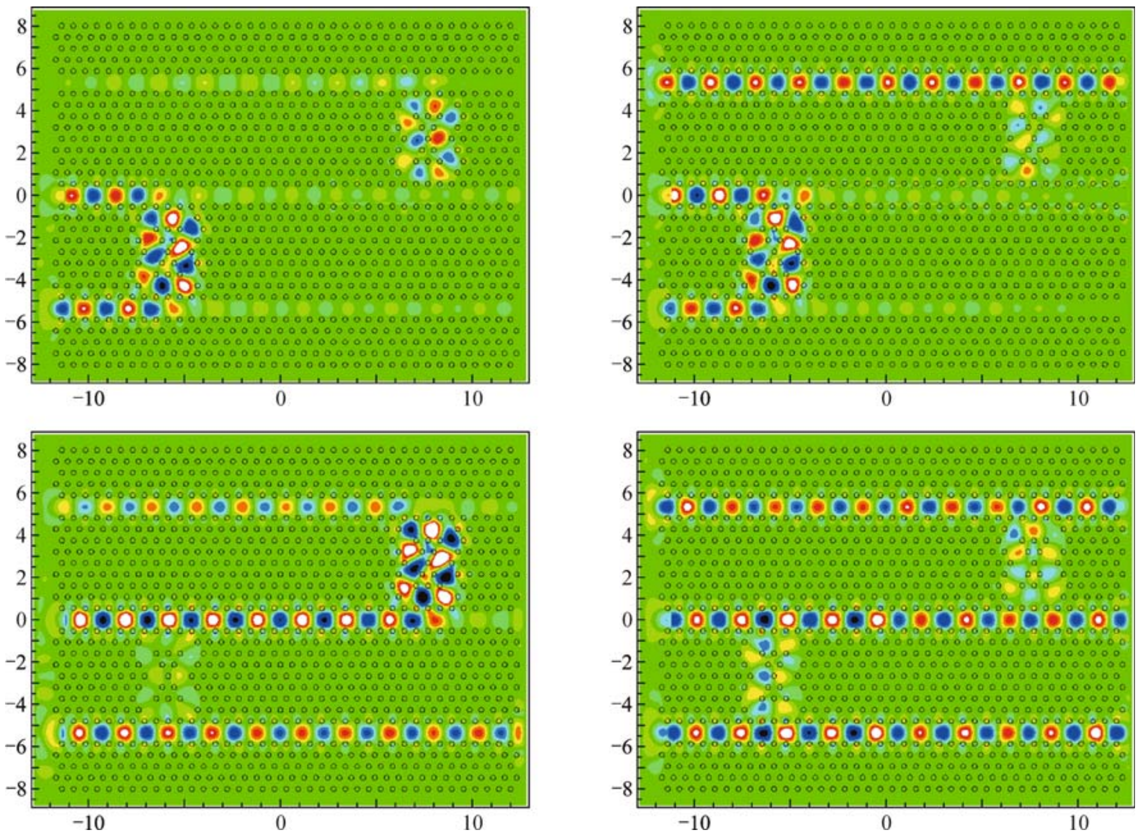

Fig. 6 Distribution of field in four state for proposed AND gate

Table 1 Truth table for proposed AND gate

A	B	output
0	0	0
0	1	0
1	0	0
1	1	1

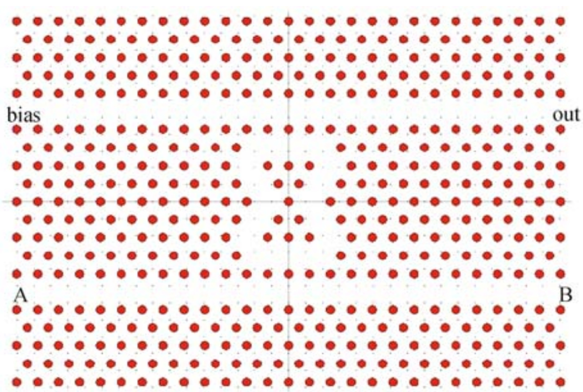

Fig. 7 OR gate structure based on photonic crystal ring resonators

Therefore, the bias keeps its path into the output. However, when the inputs do not carry any optical field the bias couples to the ring and drops to the lower waveguide. Details of propagation of optical beams for different modes of inputs are shown in Fig. 8. The true table of proposed gate is shown in Table 2.

Table 2 OR gate operating modes

A	B	output
0	0	0
0	1	1
1	0	1
1	1	1

2.4 NOT gate

The basic structure we use to design all-optical NOT logic gate, is 21×27 hexagonal array of dielectric rods in air substrate. The refractive index and the radius of the dielectric rods are 3.46 and 124 nm, respectively. Lattice constant of structure is fixed on 16 nm. The structure is similar to the one which used to design of OR gate. Hence, the band structure and the range of band gaps will be same as the OR gate structure.

Proposed NOT gate structure is shown in Fig. 9, and is formed of a ring resonator and two waveguides. This structure has two inputs, bias and A, and one output. Bias

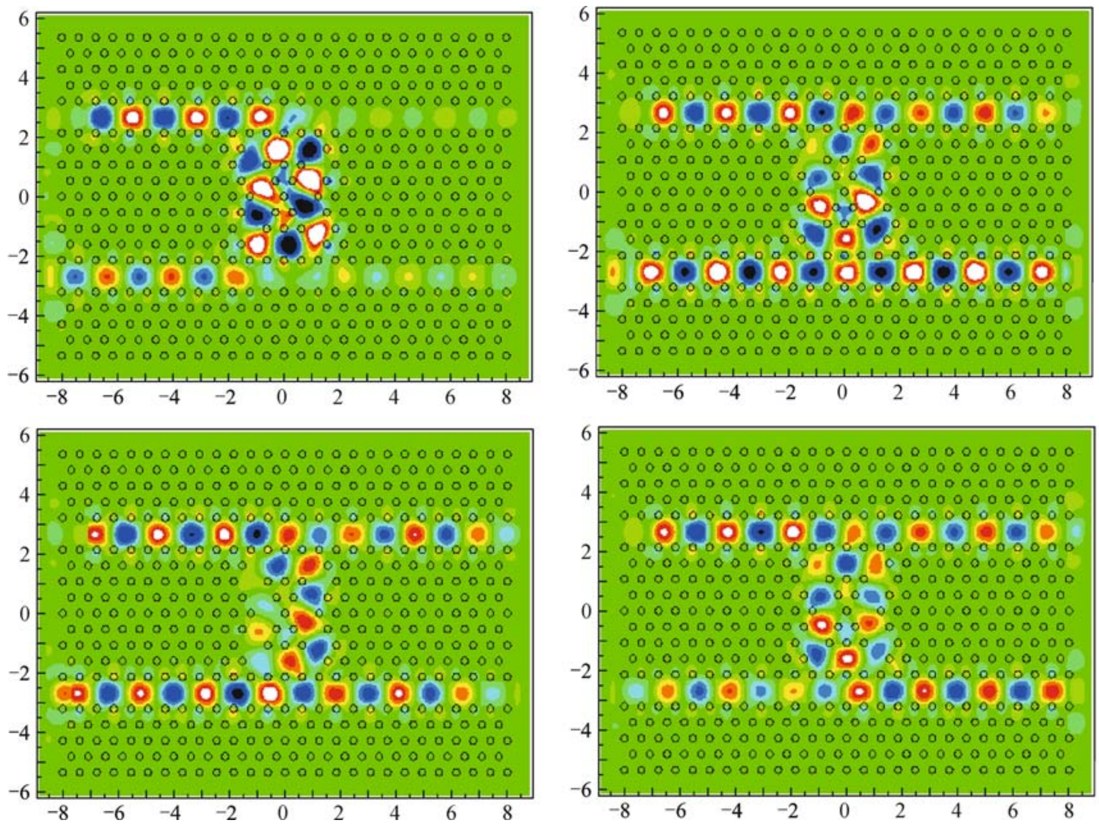

Fig. 8 Proposed OR gate procedure for four different input

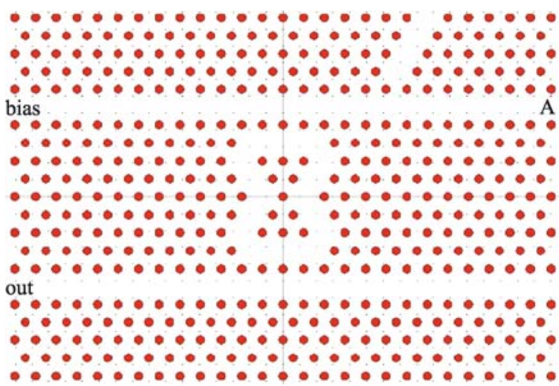

Fig. 9 Proposed NOT gate structure based on photonic crystal ring resonators

port is as bias or input power port. A is as logical input port of this gate. When there is no input, the optical field of bias couples to output through the ring resonator and the output is in high state. For the case that there is an optical incidence beam from input A, a high-intensity light enters the ring and the resonant wavelength changes. Hence, no light drops to lower waveguide and the output is in low state. This means that the structure operates as an optical NOT gate. Details of operation are shown in Fig. 10. By using a relatively high power bias, the threshold power for operation of our proposed gates is considerably decreased comparing to the results of [12,13].

3 Conclusion

In this paper, using a basic ring resonator structure we proposed designs for AND, OR, and NOT all optical logic gates. Our structures for designing optical gates are based on photonic crystal ring resonator which employs non-linear Kerr effect for operation. This effect occurs when two input beams are simultaneously enter the resonant cavity, and because of increase in optical field, the refractive index changes and consequently the resonant wavelength shifts. To do so, a bias input was introduced and defined with a wavelength identical to resonance wavelength of ring. When another input set to high and simultaneously enter the ring, it can change the transmission spectra and the propagation of light is controlled. Using this property and setting the bias to higher power, the all optical gates are designed and the results show that the proposed structures require lower input power for operation.

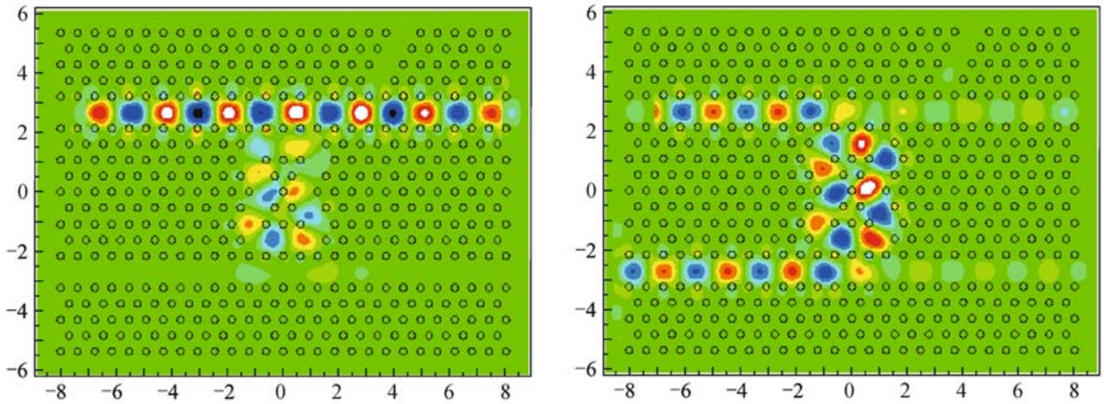

Fig. 10 Proposed NOT gate procedure for two different input

References

1. Sakoda K. Optical Properties of Photonic Crystals. Beilin: Springer, 2005
2. Ozbay E, Guven K, Cubukcu E, Aydin K, Alici B K. Negative refraction and subwavelength focusing using photonic crystals. Modern Physics Letters B, 2004, 18(25): 1275–1291
3. Joannopoulos J D, Johnson S G, Winn J N, Meade R D. Photonic Crystals: Molding the Flow of Light. Princeton: Princeton University Press, 2011
4. Yablonovitch E. Inhibited spontaneous emission in solid-state physics and electronics. Physical Review Letters, 1987, 58(20): 2059–2062
5. Qiang Z, Zhou W, Soref R A. Optical add-drop filters based on photonic crystal ring resonators. Optics Express, 2007, 15(4): 1823–1831
6. Seif-Dargahi H, Zavvari M, Alipour-Banaei H.Very compact photonic crystal resonant cavity for all optical filtering. Journal of Theoretical and Applied Physics, 2014, 8(4): 183 – 188
7. Alipour-Banaei H, Mehdizadeh F, Serajmohammadi S.A novel 4-channel demultiplexer based on photonic crystal ring resonators. Optik-International Journal for Light and Electron Optics, 2013, 124(23): 5964–5967
8. Lin W P, Hsu Y F, Kuo H L, Beckwith A, Palenskis V, Kumar C, Kirori Z, Ogutu J, Kumar R, Das D. Design of optical nor logic gates using two dimension photonic crystals. American Journal of Modern Physics, 2013, 2(3): 144–147
9. Danaei M, Kaatuzian H. Design and simulation of an all-optical photonic crystal AND gate using nonlinear Kerr effect. Optical and Quantum Electronics, 2012, 44: 27–34
10. Yaghoubi E, Ashrafbakhtiar L, Hamidisangdehi S, Adami A. A novel design for all-optical NAND/NOR/XOR gates based on nonlinear directional coupler. Journal of Advances in Computer Research, 2011, 2(4): 51–59
11. Melnichuk M, Wood L T. Direct kerr electro-optic effect in noncentrosymmetric materials. Physical Review A., 2010, 82(1): 013821
12. Andalib P, Granpayeh N. All-optical ultracompact photonic crystal AND gate based on nonlinear ring resonators. Journal of the Optical Society of America B, Optical Physics, 2009, 26(1): 10–16
13. Andalib P, Granpayeh N. All-optical ultra-compact photonic crystal NOR gate based on nonlinear ring resonators. Journal of Optics A, Pure and Applied Optics, 2009, 11(8): 085203
14. Bai J, Wang J, Jiang J, Chen X, Li H, Qiu Y, Qiang Z. Photonic NOT and NOR gates based on a single compact photonic crystal ring resonator. Applied Optics, 2009, 48(36): 6923–6927
15. Noshad M, Abbasi A, Ranjbar R, Kheradmand R. Novel all-optical logic gates based on photonic crystal structure. Journal of Physics: Conference Series, 2012, 350(1): 179–187
16. Gedney S D. Introduction to the finite-difference time-domain (FDTD) method for electromagnetics. Synthesis Lectures on Computational Electromagnetics, 2011, 6(1): 1–250
17. Djavid M, Ghaffari A, Monifi F, Abrishamian M S. T-shaped channel-drop filters using photonic crystal ring resonators. Physica E, Low-Dimensional Systems and Nanostructures, 2008, 40(10): 3151–3154
18. Alipour-Banaei H, Mehdizadeh F, Hassangholizadeh-Kashtiban M. A new proposal for PCRR-based channel drop filter using elliptical rings. Physica E, Low-Dimensional Systems and Nanostructures, 2014, 56: 211–215
19. Pezeshki H, Ahmadi V.Nanoscale effects on multichannel add/drop filter based on 2-D photonic crystal ring-resonator heterostructure. Journal of Theoretical and Applied Physics, 2012, 6(1): 1–6
20. Djavid M, Monifi F, Ghaffari A, Abrishamian M. A new broadband L-shaped bend based on photonic crystal ring resonators. In: Progressing of Electromagnetics Research Symposium, Hangzhou, China, 2008, 1097–1099
21. Taalbi A, Bassou G, Youcef Mahmoud M.New design of channel drop filters based on photonic crystal ring resonators. Optik-International Journal for Light and Electron Optics, 2013, 124(9): 824–827

Ashkan Pashamehr received the M.Sc. degree in electronic engineering from Islamic Azad University, Ahar,Iran, in 2013. His M.Sc. thesis focused on the "Design and simulation of logical gates based on photonic crystals". His research interests include ring resonators and wave-guides structures and photonic crystals.

Mahdi Zavvari received the B.S. degree from Tabriz University in 2004 and M.S. and Ph.D. degrees from Islamic Azad University science and research branch in 2007 and 2012, respectively all in electronic engineering. He is currently academic staff of Urmia branch, Islamic Azad University. His research interests are quantum dot/ring photodetectors, single photon detectors, avalanche photodiodes and photonic crystal based optical devices.

Hamed Alipour-Banaei received his M. Sc. and Ph.D. degrees from University of Tabriz, Iran. He is currently assistant professor in Islamic Azad University, Tabriz Branch, Faculty of Engineering. His research interests are optical devices, equipments and materials, optical fibers, and optical fiber nonlinear effects. He is the author or co-author of more than 60 journal and conference papers.