Optica Applicata, Vol. XLIX, No. 3, 2019
DOI: 10.5277/oa190310

An all optical majority gate using nonlinear photonic crystal based ring resonators

Amir POURSALEH[1, 2], Alireza ANDALIB[2*]

[1]Department of Electrical Engineering, East Azarbayjan Science and Research Branch, Islamic Azad University, Tabriz, Iran

[2]Department of Electrical Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran

[*]Corresponding author: andalib@iaut.ac.ir

Optical logics will play a crucial role in the next generation all optical data processing networks. Therefore an all optical majority gate will be designed by using nonlinear photonic crystal ring resonators. For realizing the proposed structure we need three nonlinear resonant rings. In order to make nonlinear resonant rings, we used chalcogenide glass as the dielectric material for the dielectric rods. The output port of the proposed structure will be active only when two or three logic input ports are active. The rise and fall time values of the proposed structure are about 2 and 1 ps, respectively. The total footprint of the proposed structure is about 1287 μm^2.

Keywords: majority gate, photonic crystal, Kerr effect, ring resonator.

1. Introduction

High bandwidth and high bit rates are the main advantages of all optical logics compared with traditional CMOS based logics [1]. Therefore there has been a strong desire toward designing all optical structures most recently. As a result, so many various solutions and mechanisms have been proposed for realizing optical devices. One can name semiconductor optical amplifiers [2], Mach–Zehnder interferometers [3] and photonic crystals (PhCs) [4, 5] as the most common examples.

Photonic crystals have photonic band gaps (PBGs) [6–8], they are scalable and do not need electrical bias. Therefore it is possible to design different kinds of compact all optical devices. As far as we know, optical filters [9–17], demultiplexers [18–24], switches [25–31], logics [32–49], decoders [50, 51], flip-flops [52] and data convertors [53–60] have been designed previously.

A common method used for designing PhC-based logic gates is combining the nonlinear Kerr effect with the resonant properties of PhCs [61–63]. In PhCs the resonant wavelength depends on the variation of the refractive index [17, 64–67]. According to the Kerr effect, the refractive index depends on the optical power [68]. So by combining these two properties, we can perform optical switching inside PhCs [69].

Afzal *et al*. [69] designed an all optical NOR gate by cascading two PhC-based filters. Caballero *et al*. [70] designed Feynman and Majority gates by using constructive and destructive optical beams inside PhCs. Christina and Kabilan [71] used self-collimated beams for designing all optical AND, NOR, XNOR and NAND gates. Mehdizadeh and Soroosh [45] combined nonlinear photonic crystal ring resonators (PhCRRs) with optical waveguides to design a 3-port optical NOR gate. NOR and NAND gates have been designed by Alipour-Banaei *et al*. [43].

In this paper, we are going to design and propose an all optical majority gate using nonlinear PhCRRs. A typical majority gate is a logic gate with 3 input ports and 1 output port. The output port will be active when 2 or 3 input ports are active. Plane wave expansion and finite-difference time-domain methods were used for simulating the proposed structure.

The rest of the paper will be organized as follows: in Section 2, we will discuss the design procedure of the proposed structure, Section 3 will be devoted to the simulation results and finally Section 4 will contain conclusion.

2. Design procedure

The photonic crystal structure used for designing the proposed majority gate consists of a square lattice array of chalcogenide glass rods with refractive index of 3.1. The dielectric rods are arranged in *xz* plane. In this structure, the background material is air. For this rods the Kerr coefficient is about 9×10^{-17} m^2/W. The radius of the dielectric rods is $r = 0.2a$, where $a = 614$ nm is the lattice constant of the structure. For this structure, the band structure diagram has been calculated and obtained like Fig. 1. This PhC structure has PBG region at $0.31 < a/\lambda < 0.44$ in TM mode (blue colored area) which is equal to 1395 nm $< \lambda <$1980 nm.

In order to create the proposed majority gate, we need to cascade three 2-input optical OR gates. A typical optical OR gate is composed of PhCRR combined with 4 op-

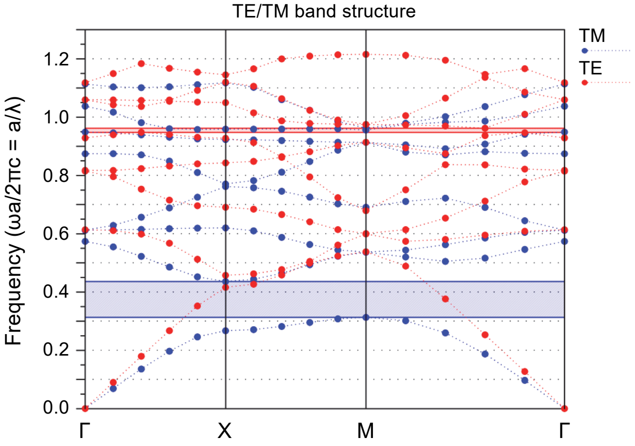

Fig. 1. Band structure diagram of the PhC.

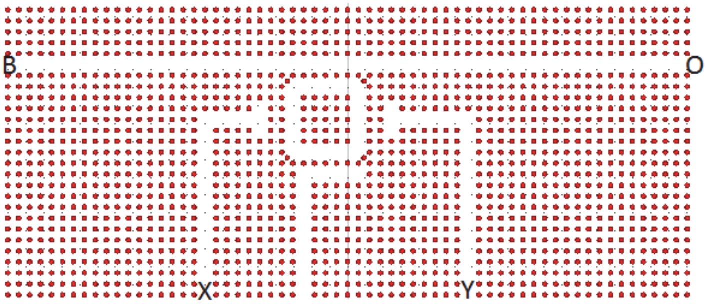

Fig. 2. All optical OR gate.

tical waveguides as shown in Fig. 2. In this structure, B is the bias port, X and Y are the input ports and O is the output port. The resonant ring was designed such that when both X and Y are inactive, it can drop the low power optical beams coming from B, so the output is active. But when one or both of X or Y ports become active, the high power optical beams from X or Y will change the resonant mode of the resonant ring so the resonant ring cannot drop the optical beam coming from B and as a result the output will be active.

The final structure for realizing the majority gate will be obtained by cascading three optical OR gates. The proposed structure is shown in Fig. 3. It consists of three resonant rings along with eight optical waveguides. The resonant rings were designed such that they can drop low power optical waves with central wavelength of 1550 nm, but they cannot drop high power optical waves. The quality factor of the resonant rings is about 500. Four rods at the corners of the resonant ring were place in order to reduce

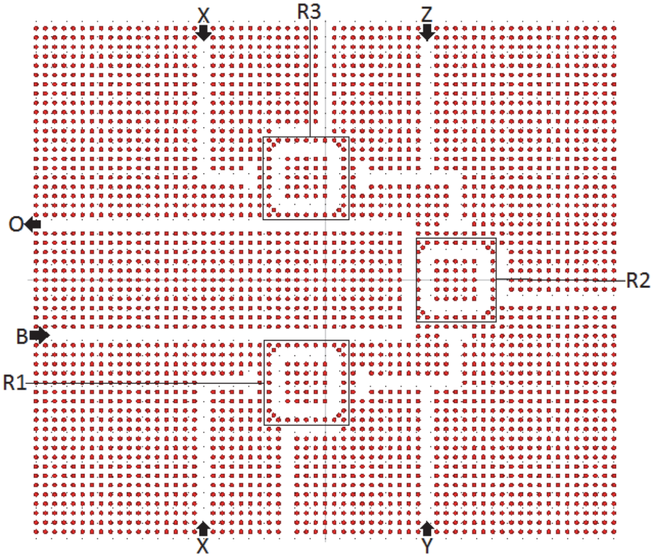

Fig. 3. All optical majority gate.

the unwanted reflection from the corners of the ring. In the proposed structure, B is the bias port, X, Y and Z are the input logic ports and O is the output port of the structure. As one can see, every resonant ring was connected to 2 of the input logic ports; R1 was connected to X and Y logic input ports, R2 was connected to Y and Z logic ports and finally R3 was connected to X and Z logic ports. The total footprint of the proposed structure is about 1287 μm^2.

3. Simulation and results

When the design procedure was completed, we should test the functionality of the proposed structure by studying its optical behavior. For this purpose we used the finite -difference time-domain method. As mentioned earlier, the proposed structure has one input port for the bias beam, and three input ports for logic input ports and finally the structure has one output port. In the bias port, we used low power optical waves, however in X, Y and Z ports we used high power optical waves. For all of the input ports the central wavelength of the optical beams is 1550 nm. For proper operation of the proposed structure, the port B always should be active. There are eight different working states for the proposed structure according to different combinations of its input ports.

When all the logic input ports are inactive, all the resonant rings are in linear region. When the optical waves coming from B reach R1, R1 drops them into its corresponding drop waveguide. As a result, no optical waves reach the output port, therefore O will be inactive (Fig. 4).

When X is active but Y and Z are inactive, due to high power optical waves coming from X, R1 cannot drop the optical waves coming from B. Therefore the optical waves travel toward R2, because Y and Z are inactive, R2 is in linear region and can drop bias waves into its corresponding drop waveguide. As a result, bias waves will not reach the output port and O will be inactive (Fig. 5).

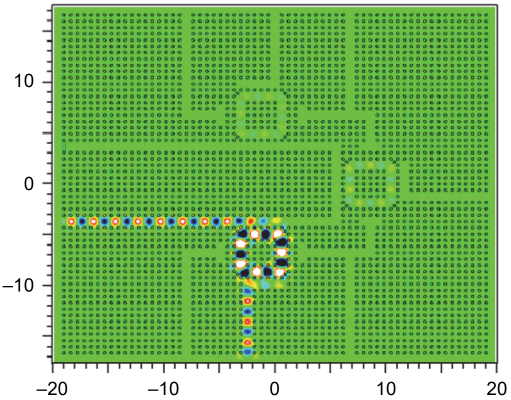

Fig. 4. Optical behavior of the proposed structure when X, Y and Z are inactive.

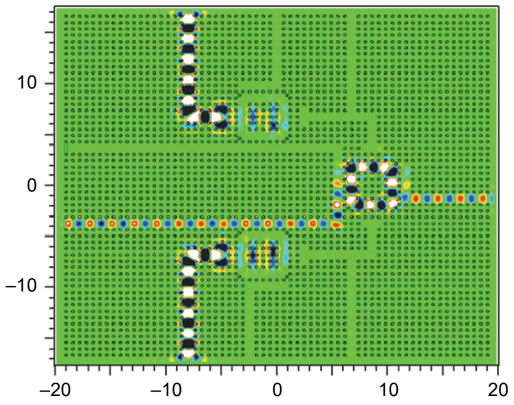

Fig. 5. Optical behavior of the proposed structure when X is active but Y and Z are inactive.

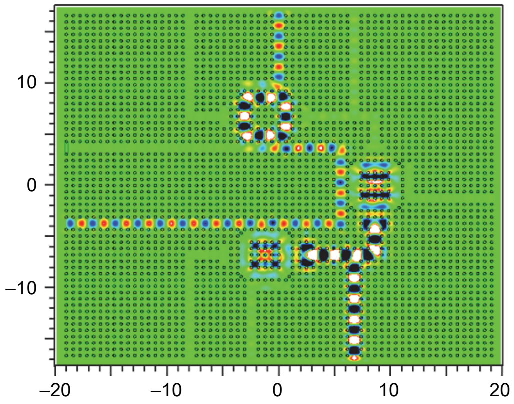

Fig. 6. Optical behavior of the proposed structure when Y is active but X and Z are inactive.

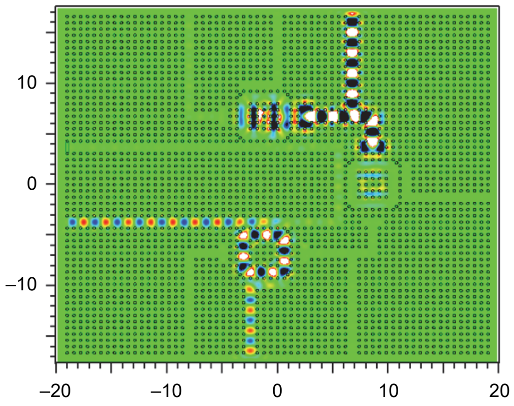

Fig. 7. Optical behavior of the proposed structure when Z is active but X and Y are inactive.

When Y is active but X and Z are inactive, due to high power optical waves coming from Y, R1 and R2 are in nonlinear region and they cannot drop the optical waves coming from B. Therefore the optical waves travel toward R3, because X and Z are inactive, R3 is in linear region and can drop bias waves into its corresponding drop waveguide. As a result, bias waves will not reach the output port and O will be inactive (Fig. 6).

When Z is active but X and Y are inactive, due to the lack of high power optical waves near R1, it is in linear region and it can drop the optical waves coming from B. Therefore the optical waves travel toward R3, because X and Z are inactive, R3 is in linear region and can drop bias waves into its corresponding drop waveguide. As a result, bias waves will not reach the output port and O will be inactive (Fig. 7).

When X and Y are active but Z is inactive, due to high optical power coming from X and Y, all the three resonant rings are in nonlinear region and none of them can drop the bias waves. As the result, the bias waves travel toward the output power and O will be active (Fig. 8).

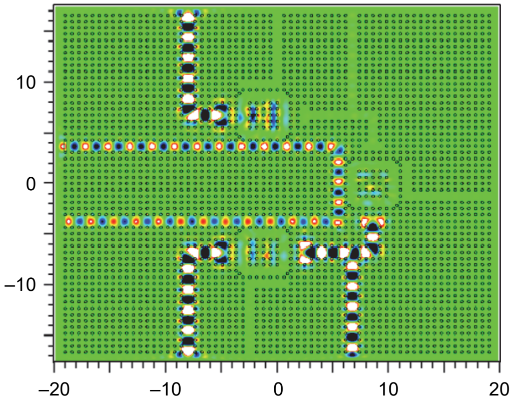

Fig. 8. Optical behavior of the proposed structure when X and Y are active but Z is inactive.

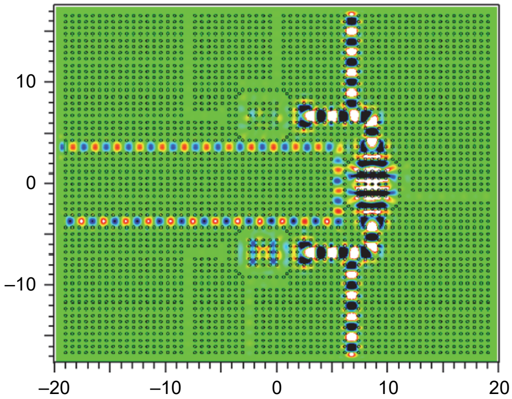

Fig. 9. Optical behavior of the proposed structure when Y and Z are active but X is inactive.

When Y and Z are active but X is inactive, due to high optical power coming from Y and Z all the three resonant rings are in nonlinear region and none of them can drop the bias waves. As the result, the bias waves travel toward the output power and O will be active (Fig. 9).

When X and Z are active but Y is inactive, due to high optical power coming from X and Z, all the three resonant rings are in nonlinear region and none of them can drop the bias waves. As the result, the bias waves travel toward the output power and O will be active (Fig. 10).

When all the input ports are active, due to high optical power coming from these ports, all the three resonant rings are in nonlinear region and none of them can drop the bias waves. As the result, the bias waves travel toward the output power and O will be active (Fig. 11).

The obtained results show that the proposed structure output port is active when 2 or 3 logic input ports are active. This means that the proposed structure can operate

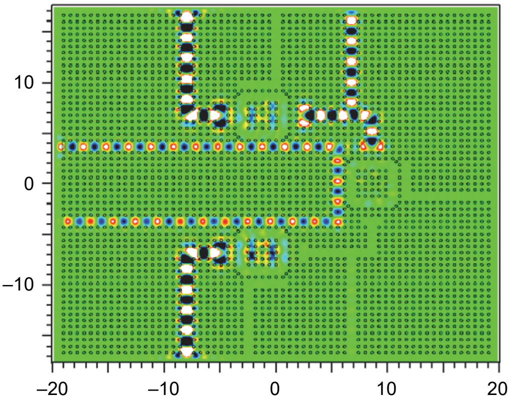

Fig. 10. Optical behavior of the proposed structure when X and Y are active but Z is inactive.

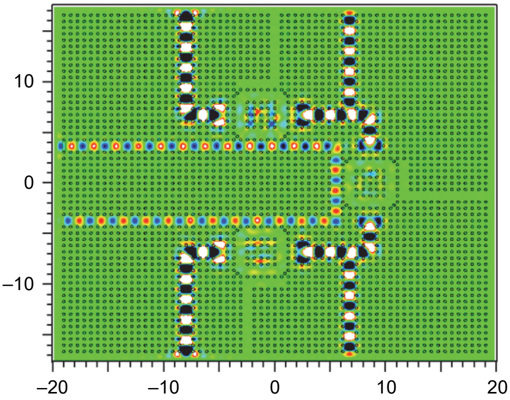

Fig. 11. Optical behavior of the proposed structure when X, Y and Z are active.

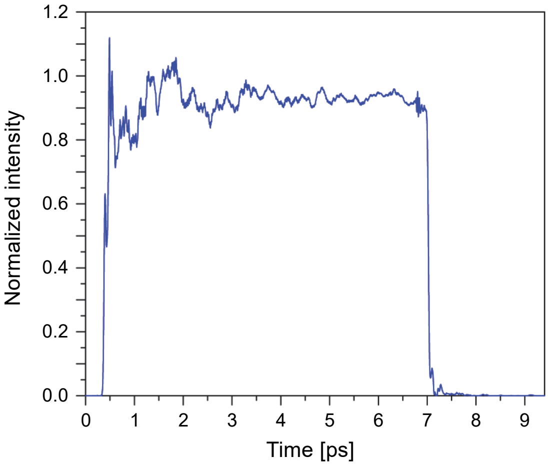

Fig. 12. Time response of the proposed structure.

as an all optical majority gate. The time response diagram of the proposed structure is shown in Fig. 12. One can observe from this figure that the rise and fall time of the proposed structure is about 2 and 1 ps, respectively.

4. Conclusion

In this paper we used a nonlinear PhCRR for designing an all optical OR gate. Then by cascading three OR gates, a novel structure was proposed for realizing an all optical majority gate. The proposed structure has a bias input port and three logic control ports. Using these logic input ports, one can control whether the bias port can reach the output port or not. The output port of the proposed structure is active only when two or three logic input ports are active. The rise and fall time of the proposed structure is about 2 and 1 ps, respectively. For the proposed structure the contrast ratio is about 19 dB.

References

[1] Dutton H.J.R., *Understanding Optical Communications*, Prentice Hall PTR, 1998.

[2] Kaur S., *All optical data comparator and decoder using SOA-based Mach–Zehnder interferometer*, Optik **124**(17), 2013, pp. 2650–2653, DOI: 10.1016/j.ijleo.2012.07.041.

[3] Zhang Y., Yu Y., Du C., Ruan S., Chen X., Huang Q., Zhou W., *Strain-independent high-temperature sensor with a suspended-core fiber based Mach–Zehnder interferometer*, Optical Fiber Technology **29**, 2016, pp. 6–12, DOI: 10.1016/j.yofte.2016.01.006.

[4] John S., *Strong localization of photons in certain disordered dielectric superlattices*, Physical Review Letters **58**(23), 1987, pp. 2486–2489, DOI: 10.1103/PhysRevLett.58.2486.

[5] Yablonovitch E., *Inhibited spontaneous emission in solid-state physics and electronics*, Physical Review Letters **58**(20), 1987, pp. 2059–2062, DOI: 10.1103/PhysRevLett.58.2059.

[6] Liu D., Gao Y., Tong A., Hu S., *Absolute photonic band gap in 2D honeycomb annular photonic crystals*, Physics Letters A **379**(3), 2015, pp. 214–217, DOI: 10.1016/j.physleta.2014.11.030.

[7] Alipour-Banaei H., Serajmohammadi S., Mehdizadeh F., Andalib A., *Band gap properties of two -dimensional photonic crystal structures with rectangular lattice*, Journal of Optical Communications **36**(2), 2015, pp. 109–114, DOI: 10.1515/joc-2014-0049.

[8] Alipour-Banaei H., Mehdizadeh F., *Bandgap calculation of 2D hexagonal photonic crystal structures based on regression analysis*, Journal of Optical Communications **34**(4), 2013, pp. 285–293, DOI: 10.1515/joc-2013-0033.

[9] Saghirzadeh Darki B., Granpayeh N., *Improving the performance of a photonic crystal ring-resonator-based channel drop filter using particle swarm optimization method*, Optics Communications **283**(20), 2010, pp. 4099–4103, DOI: 10.1016/j.optcom.2010.06.013.

[10] Musavizadeh S.M., Soroosh M., Mehdizadeh F., *Optical filter based on photonic crystal*, Indian Journal of Pure and Applied Physics **53**(11), 2015, pp. 736–739.

[11] Alipour-Banaei H., Serajmohammadi S., Mehdizadeh F., Hassangholizadeh-Kashtiban M., *Special optical communication filter based on Thue–Morse photonic crystal structure*, Optica Applicata **46**(1), 2016, pp. 145–152, DOI: 10.5277/oa160113.

[12] Sahel S., Amri R., Bouaziz L., Gamra D., Lejeune M., Benlahsen M., Zellama K., Bouchriha H., *Optical filters using Cantor quasi-periodic one dimensional photonic crystal based on Si/SiO*$_2$, Superlattices and Microstructures **97**, 2016, pp. 429–438, DOI: 10.1016/j.spmi.2016.07.007.

[13] Alipour-Banaei H., Mehdizadeh F., Hassangholizadeh-Kashtiban M., *Important effect of defect parameters on the characteristics of Thue–Morse photonic crystal filters*, Advances in OptoElectronics, 2013, article ID 856148, DOI: 10.1155/2013/856148.

[14] Ren C., Wang P., Cheng L., Feng S., Gan L., Li Z., *Multichannel W3 Y-branch filter in a two dimensional triangular-lattice photonic crystal slab*, Optik **125**(24), 2014, pp. 7203–7206, DOI: 10.1016/j.ijleo.2014.07.139.

[15] Wang Y., Chen D., Zhang G., Wang J., Tao S., *A super narrow band filter based on silicon 2D photonic crystal resonator and reflectors*, Optics Communications **363**, 2016, pp. 13–20, DOI: 10.1016/j.optcom.2015.10.070.

[16] Mansouri-Birjandi M.A., Tavousi A., Ghadrdan M., *Full-optical tunable add/drop filter based on nonlinear photonic crystal ring resonators*, Photonics and Nanostructures – Fundamentals and Applications **21**, 2016, pp. 44–51, DOI: 10.1016/j.photonics.2016.06.002.

[17] Tavousi A., Mansouri-Birjandi M.A., Ghadrdan M., Ranjbar-Torkamani M., *Application of photonic crystal ring resonator nonlinear response for full-optical tunable add–drop filtering*, Photonic Network Communications **34**(1), 2017, pp. 131–139, DOI: 10.1007/s11107-016-0680-x.

[18] Mehdizadeh F., Soroosh M., *A new proposal for eight-channel optical demultiplexer based on photonic crystal resonant cavities*, Photonic Network Communications **31**(1), 2016, pp. 65–70, DOI: 10.1007/s11107-015-0531-1.

[19] Mehdizadeh F., Soroosh M., Alipour-Banaei H., *An optical demultiplexer based on photonic crystal ring resonators*, Optik **127**(20), 2016, pp. 8706–8709, DOI: 10.1016/j.ijleo.2016.06.086.

[20] Venkatachalam K., Robinson S., Umamaheswari S., *Two dimensional photonic crystal based four channel demultiplexer for ITU.T.G 694.2 CWDM systems*, International Journal of Photonics and Optical Technology **2**(3), 2016, pp. 37–41.

[21] Rakhshani M.R., Mansouri-Birjandi M.A., *Design and simulation of wavelength demultiplexer based on heterostructure photonic crystals ring resonators*, Physica E: Low-dimensional Systems and Nanostructures **50**, 2013, pp. 97–101, DOI: 10.1016/j.physe.2013.03.003.

[22] Talebzadeh R., Soroosh M., Daghooghi T., *A 4-channel demultiplexer based on 2D photonic crystal using line defect resonant cavity*, IETE Journal of Research **62**(6), 2016, pp. 866–872, DOI: 10.1080/03772063.2016.1217175.

[23] Rawal S., Sinha R.K., *Design, analysis and optimization of silicon-on-insulator photonic crystal dual band wavelength demultiplexer*, Optics Communications **282**(19), 2009, pp. 3889–3894, DOI: 10.1016/j.optcom.2009.06.046.

[24] Bazargani H.P., *Proposal for a 4-channel all optical demultiplexer using 12-fold photonic quasicrystal*, Optics Communications **285**(7), 2012, pp. 1848–1853, DOI: 10.1016/j.optcom.2011.12.002.

[25] Yanik M.F., Fan S., Soljačić M., Joannopoulos J.D., *All-optical transistor action with bistable switching in a photonic crystal cross-waveguide geometry*, Optics Letters **28**(24), 2003, pp. 2506–2508, DOI: 10.1364/OL.28.002506.

[26] Mehdizadeh F., Soroosh M., Alipour-Banaei H., *A novel proposal for optical decoder switch based on photonic crystal ring resonators*, Optical and Quantum Electronics **48**(1), 2016, article ID 20, DOI: 10.1007/s11082-015-0313-0.

[27] Mehdizadeh F., Alipour-Banaei H., Serajmohammadi S., *Study the role of non-linear resonant cavities in photonic crystal-based decoder switches*, Journal of Modern Optics **64**(13), 2017, pp. 1233–1239, DOI: 10.1080/09500340.2016.1275854.

[28] Ouahab I., Rafah N., *A novel all optical 4×2 encoder switch based on photonic crystal ring resonators*, Optik **127**(19), 2016, pp. 7835–7841, DOI: 10.1016/j.ijleo.2016.05.080.

[29] Zhang Y., Zhang Y., Li B., *Optical switches and logic gates based on self-collimated beams in two-dimensional photonic crystals*, Optics Express **15**(15), 2007, pp. 9287–9292, DOI: 10.1364/OE.15.009287.

[30] Zhu Z.-H., Ye W.-M., Ji J.-R., Yuan X.-D., Zen C., *High-contrast light-by-light switching and AND gate based on nonlinear photonic crystals*, Optics Express **14**(5), 2006, pp. 1783–1788, DOI: 10.1364/OE.14.001783.

[31] Alipour-Banaei H., Mehdizadeh F., Serajmohammadi S., Hassangholizadeh-Kashtiban M., *A 2*4 all optical decoder switch based on photonic crystal ring resonators*, Journal of Modern Optics **62**(6), 2015, pp. 430–434, DOI: 10.1080/09500340.2014.957743.

[32] Mehdizadeh F., Soroosh M., Alipour-Banaei H., *Proposal for 4-to-2 optical encoder based on photonic crystals*, IET Optoelectronics **11**(1), 2017, pp. 29–35, DOI: 10.1049/iet-opt.2016.0022.

[33] Hassangholizadeh-Kashtiban M., Sabbaghi-Nadooshan R., Alipour-Banaei H., *A novel all optical reversible 4×2 encoder based on photonic crystals*, Optik **126**(20), 2015, pp. 2368–2372, DOI: 10.1016/j.ijleo.2015.05.140.

[34] Moniem T.A., *All-optical digital 4 × 2 encoder based on 2D photonic crystal ring resonators*, Journal of Modern Optics **63**(8), 2016, pp. 735–741, DOI: 10.1080/09500340.2015.1094580.

[35] Alipour-Banaei H., Rabati M.G., Abdollahzadeh-Badelbou P., Mehdizadeh F., *Application of self-collimated beams to realization of all optical photonic crystal encoder*, Physica E: Low-dimensional Systems and Nanostructures **75**, 2016, pp. 77–85, DOI: 10.1016/j.physe.2015.08.011.

[36] Alipour-Banaei H., Rabati M.G., Abdollahzadeh-Badelbou P., Mehdizadeh F., *Effect of self-collimated beams on the operation of photonic crystal decoders*, Journal of Electromagnetic Waves and Applications **30**(11), 2016, pp. 1440–1448, DOI: 10.1080/09205071.2016.1202785.

[37] Shaik E. haq, Rangaswamy N., *Design of photonic crystal-based all-optical AND gate using T-shaped waveguide*, Journal of Modern Optics **63**(10), 2016, pp. 941–949, DOI: 10.1080/09500340.2015.1111455.

[38] Parandin F., Karkhanehchi M.M., *Terahertz all-optical NOR and AND logic gates based on 2D photonic crystals*, Superlattices and Microstructures **101**, 2017, pp. 253–260, DOI: 10.1016/j.spmi.2016.11.038.

[39] Shaik E., Rangaswamy N., *Multi-mode interference-based photonic crystal logic gates with simple structure and improved contrast ratio*, Photonic Network Communications **34**(1), 2017, pp. 140–148, DOI: 10.1007/s11107-016-0683-7.

[40] Jiang Y.-C., Liu S.-B., Zhang H.-F., Kong X.-K., *Reconfigurable design of logic gates based on a two-dimensional photonic crystals waveguide structure*, Optics Communications **332**, 2014, pp. 359–365, DOI: 10.1016/j.optcom.2014.07.038.

[41] Goudarzi K., Mir A., Chaharmahali I., Goudarzi D., *All-optical XOR and OR logic gates based on line and point defects in 2-D photonic crystal*, Optics and Laser Technology **78**, 2016, pp. 139–142, DOI: 10.1016/j.optlastec.2015.10.013.

[42] Chunrong Tang, Xinyu Dou, Yuxi Lin, Hongxi Yin, Bin Wu, Qingchun Zhao, *Design of all-optical logic gates avoiding external phase shifters in a two-dimensional photonic crystal based on multi-mode interference for BPSK signals*, Optics Communications **316**, 2014, pp. 49–55, DOI: 10.1016/j.optcom.2013.11.053.

[43] Alipour-Banaei H., Serajmohammadi S., Mehdizadeh F., *All optical NOR and NAND gate based on nonlinear photonic crystal ring resonators*, Optik **125**(19), 2014, pp. 5701–5704, DOI: 10.1016/j.ijleo.2014.06.013.

[44] Alipour-Banaei H., Serajmohammadi S., Mehdizadeh F., *All optical NAND gate based on nonlinear photonic crystal ring resonators*, Optik **130**, 2017, pp. 1214–1221, DOI: 10.1016/j.ijleo.2016.11.190.

[45] Mehdizadeh F., Soroosh M., *Designing of all optical NOR gate based on photonic crystal*, Indian Journal of Pure and Applied Physics **54**(1), 2016, pp. 35–39.

[46] Alipour-Banaei H., Seif-Dargahi H., *Photonic crystal based 1-bit full-adder optical circuit by using ring resonators in a nonlinear structure*, Photonics and Nanostructures – Fundamentals and Applications **24**, 2017, pp. 29–34, DOI: 10.1016/j.photonics.2017.03.001.

[47] Neisy M., Soroosh M., Ansari-Asl K., *All optical half adder based on photonic crystal resonant cavities*, Photonic Network Communications **35**(2), 2018, pp. 245–250, DOI: 10.1007/s11107-017-0736-6.

[48] Cheraghi F., Soroosh M., Akbarizadeh G., *An ultra-compact all optical full adder based on nonlinear photonic crystal resonant cavities*, Superlattices and Microstructures **113**, 2018, pp. 359–365, DOI: 10.1016/j.spmi.2017.11.017.

[49] Jalali-Azizpoor M.R., Soroosh M., Seifi-Kavian Y., *Application of self-collimated beams in realizing all-optical photonic crystal-based half-adder*, Photonic Network Communications **36**(3), 2018, pp. 344–349, DOI: 10.1007/s11107-018-0786-4.

[50] Daghooghi T., Soroosh M., Ansari-Asl K., *A novel proposal for all-optical decoder based on photonic crystals*, Photonic Network Communications **35**(3), 2018, pp. 335–341, DOI: 10.1007/s11107-017-0746-4.

[51] Daghooghi T., Soroosh M., Ansari-Asl K., *Ultra-fast all-optical decoder based on nonlinear photonic crystal ring resonators*, Applied Optics **57**(9), 2018, pp. 2250–2257, DOI: 10.1364/AO.57.002250.

[52] Zamanian-Dehkordi S.S., Soroosh M., Akbarizadeh G., *An ultra-fast all-optical RS flip-flop based on nonlinear photonic crystal structures*, Optical Review **25**(4), 2018, pp. 523–531, DOI: 10.1007/s10043-018-0443-2.

[53] Youssefi B., Moravvej-Farshi M.K., Granpayeh N., *Two bit all-optical analog-to-digital converter based on nonlinear Kerr effect in 2D photonic crystals*, Optics Communications **285**(13–14), 2012, pp. 3228–3233, DOI: 10.1016/j.optcom.2012.02.081.

[54] Tavousi A., Mansouri-Birjandi M.A., Saffari M., *Successive approximation-like 4-bit full-optical analog-to-digital converter based on Kerr-like nonlinear photonic crystal ring resonators*, Physica E: Low-dimensional Systems and Nanostructures **83**, 2016, pp. 101–106, DOI: 10.1016/j.physe.2016.04.007.

[55] Mehdizadeh F., Soroosh M., Alipour-Banaei H., Farshidi E., *All optical 2-bit analog to digital converter using photonic crystal based cavities*, Optical and Quantum Electronics **49**(1), 2017, article ID 38, DOI: 10.1007/s11082-016-0880-8.

[56] Mehdizadeh F., Soroosh M., Alipour-Banaei H., Farshidi E., *Ultra-fast analog-to-digital converter based on a nonlinear triplexer and an optical coder with a photonic crystal structure*, Applied Optics **56**(7), 2017, pp. 1799–1806, DOI: 10.1364/AO.56.001799.

[57] Mehdizadeh F., Soroosh M., Alipour-Banaei H., Farshidi E., *A novel proposal for all optical analog-to-digital converter based on photonic crystal structures*, IEEE Photonics Journal **9**(2), 2017, article ID 4700311, DOI: 10.1109/JPHOT.2017.2690362.

[58] Miao B., Chen C., Sharkway A., Shi S., Prather D.W., *Two bit optical analog-to-digital converter based on photonic crystals*, Optics Express **14**(17), 2006, pp. 7966–7973, DOI: 10.1364/OE.14.007966.

[59] Fasihi K., *All-optical analog-to-digital converters based on cascaded 3-dB power splitters in 2D photonic crystals*, Optik **125**(21), 2014, pp. 6520–6523, DOI: 10.1016/j.ijleo.2014.08.030.

[60] Xu C., Liu X., *Photonic analog-to-digital converter using soliton self-frequency shift and interleaving spectral filters*, Optics Letters **28**(12), 2003, pp. 986–988, DOI: 10.1364/OL.28.000986.

[61] Memarzadeh Isfahani B., Ahamdi Tameh T., Granpayeh N., Maleki Javan A.R., *All-optical NOR gate based on nonlinear photonic crystal microring resonators*, Journal of the Optical Society of America B **26**(5), 2009, pp. 1097–1102, DOI: 10.1364/JOSAB.26.001097.

[62] Bao J., Xiao J., Fan L., Li X., Hai Y., Zhang T., Yang C., *All-optical NOR and NAND gates based on photonic crystal ring resonator*, Optics Communications **329**, 2014, pp. 109–112, DOI: 10.1016/j.optcom.2014.04.076.

[63] Danaie M., Kaatuzian H., *Design and simulation of an all-optical photonic crystal AND gate using nonlinear Kerr effect*, Optical and Quantum Electronics **44**(1–2), 2012, pp. 27–34, DOI: 10.1007/s11082-011-9527-y.

[64] Alipour-Banaei H., Mehdizadeh F., *Significant role of photonic crystal resonant cavities in WDM and DWDM communication tunable filters*, Optik **124**(17), 2013, pp. 2639–2644, DOI: 10.1016/j.ijleo.2012.07.029.

[65] Alipour-Banaei H., Jahanara M., Mehdizadeh F., *T-shaped channel drop filter based on photonic crystal ring resonator*, Optik **125**(18), 2014, pp. 5348–5351, DOI: 10.1016/j.ijleo.2014.06.056.

[66] Taalbi A., Bassou G., Youcef Mahmoud M., *New design of channel drop filters based on photonic crystal ring resonators*, Optik **124**(9), 2013, pp. 824–827, DOI: 10.1016/j.ijleo.2012.01.045.

[67] Youcef Mahmoud M., Bassou G., Taalbi A., *A new optical add–drop filter based on two-dimensional photonic crystal ring resonator*, Optik **124**(17), 2013, pp. 2864–2867, DOI: 10.1016/j.ijleo.2012.08.072.

[68] Petrenko A.D., *Nonlinear Kerr effect in magnetic crystals*, Physics of the Solid State **41**(4), 1999, pp. 591–594, DOI: 10.1134/1.1130831.

[69] Afzal S., Ahmadi V., Ebnali-Heidari M., *All-optical tunable photonic crystal NOR gate based on the nonlinear Kerr effect in a silicon nanocavity*, Journal of the Optical Society of America B **30**(9), 2013, pp. 2535–2539, DOI: 10.1364/JOSAB.30.002535.

[70] Pedraza Caballero L.E., Vasco J.P., Guimarães P.S.S., Vilela Neto O.P., *All-optical Majority and Feynman gates in photonic crystals*, [In] *2015 30th Symposium on Microelectronics Technology and Devices (SBMicro)*, 2015, DOI: 10.1109/SBMicro.2015.7298150.

[71] Christina X.S., Kabilan A.P., *Design of optical logic gates using self-collimated beams in 2D photonic crystal*, Photonic Sensors **2**(2), 2012, pp. 173–179, DOI: 10.1007/s13320-012-0054-7.

Received May 28, 2018
in revised form July 29, 2018