Islamic Azad University

Journal of
Optoelectronical Nanostructures

Spring 2022 / Vol. 7, No. 2

Research Paper

Designing of All-Optical Subtractor via PC-Based Resonators

Forogh Pakrai [1], Mohammad Soroosh *,[2], Jabbar Ganji [1]

[1] Department of Electrical Engineering, Mahshahr Branch, Islamic Azad University, Mahshahr, Iran.
[2] Department of Electrical Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran.

Received: 22 Mar. 2022
Revised: 18 May. 2022
Accepted: 10 Jun. 2022
Published: 15 Jun. 2022

Use your device to scan and read the article online

Keywords:
Half-subtractor, Optical Kerr effect, Photonic crystal, Resonant ring.

Abstract Using a photonic crystal array, an all-optical half-subtractor has been designed that consists of four resonant rings and some waveguides which connect two input ports to output ports. The silicon rods with a period of 0.631 μm are arranged in the form of a square. Concerning the four working states of the device, different radii of nonlinear rods inside the resonators have been chosen. This issue makes the different switching thresholds for the rings and results in the correct dropping operation for optical waves. Unlike the previous works, each bit is defined to one port, and the input ports have equal power. The maximum rise time and the contrast ratio of the presented circuit are 3.5 ps and 8.45 dB, respectively. The fast response and small size are the main advantages of the presented subtractor. The obtained results demonstrates that the designed device has an acceptable performance which is proper for optical applications.

Citation: Forogh Pakrai, Mohammad Soroosh, Jabbar Ganji. Designing of all-optical subtractor via PC-based resonators **Journal of Optoelectronical Nanostructures. 2022; 7 (2): 21- 36. DOI: 10.30495/JOPN.2022.29545.1246**

***Corresponding author**: Mohammad Soroosh
Address: Department of Electrical Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran. **Tell:** 00989122965969. **Email:** m.soroosh@scu.ac.ir

1. INTRODUCTION

All-optical processing has attracted much attention to design of all-optical devices. For guiding and manipulating the light, a proper medium should be employed. Photonic crystal (PC) [1,2] is the regular array of dielectrics, by which confining the propagation of light rays inside the desired waveguides is achievable [3,4]. To couple the waves between two waveguides, resonant rings have been used. The nonlinear bars inside the rings make to approach the different switching threshold [5-9]. Based on this property, different kinds of PC-based elements such as optical filters [10-13], demultiplexers [14-17], decoders [18-21], encoders [22,23], adders [24-28], comparators [29-32], flip-flops [33,34], multiplexers [35], and data converters [36-41] have been designed.

For creating an all-optical computation system, half-subtractors should be designed as the fundamental blocks. The first PC-based half-subtractor (HS) was created by connecting some waveguides inside a hexagonal lattice. [42]. Although they succeeded in obtaining the time response of 0.1 ps, the circuit had difficulty employing in optical circuits. In this circuit, to obtain the subtraction operation, the power of an input port should be 1.5 times one at the other port. This is known as a challenge for connecting it to another device because the gap of margins should be matched. Moradi [43] proposed a PC-based subtractor including three nonlinear resonant rings. In this circuit, they used two ports for one bit to realize the subtraction operation. Concerning different values of delay time in different paths, the synchronization of two ports for one input bit is a significant challenge. The rise time (t_r) of 3 ps was reported for this circuit. Askarian et al. [44] designed a half-subtractor using one nonlinear ring resonator. In spite of having t_r=1 ps, like the previous work, two ports were used for each input bit. Askarian et al. [45] presented an optical half-subtractor (OHS) employing PSK technique. This circuit does not need threshold switching or high values of optical powers. They used two optical sources along with the input signals two extra ports for reference signals. The rise time was 2 ps. Recently, Namdari et al. [46] have realized an optical half-subtractor including nonlinear resonators to send the light to the output ports. Although t_r=1.5 ps, the small radii used in the circuit can be a challenge for the feasibility of the fabrication.

The all-optical half-subtractor, proposed in this work, has two nonlinear resonant rings to guide waves inside correct paths. Considering the difficulties of the previous works, the presented circuit has improved them. Unlike them, in the proposed circuit, equal powers are applied to the input ports and one port is assigned to each input bit. Considering the fabricated photonic crystal structures, the radii of the bars are compatible with the common fabrication techniques. The t_r and C_r are 3.5 ps and 8.45 dB, respectively.

2. THE HALF-SUBTRACTOR

For the proposed half-subtractor, a 2D array of Si rods with 82 rows and 57 columns has been used. For the 2D PC, 3.46 and 0.126 μm were chosen for refractive index and radii of the bars. The spatial period is 0.631 μm. Assuming a=631 nm, the circuit includes two bandgaps of 853-876 nm and 1502-2254 nm (figure 1). A wavelength of 1550 nm which is inside the larger photonic bandgap will be used to the input light. So, these waves are allowed to transmit through the designed waveguides.

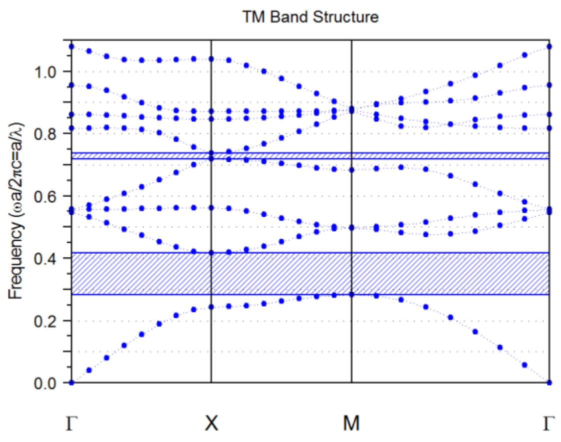


Fig. 1. Band gap region of the 2D PC.

Table I shows truth table of a HS. If one of the inputs be at a high level, port D will be at logic 1. So, both inputs were connected to a waveguide through a combiner and guided toward port D via a resonant ring. When X or Y becomes ON, the waveguide's optical intensity satisfies the threshold intensity for coupling operation, and port D is activated. Concerning the table, port B is activated for state 2 (X=0,Y=1). One part of the signal Y should be used to activate port B, so a resonant ring is needed to couple a part of signal Y. Another part of signal Y should also be guided toward port B through a resonant ring for enhancement of optical intensity at port B. Based on this strategy, a circuit was proposed for the photonic crystal-based half-subtractor.

TABLE I

ALL WORKING STATES OF A HALF-SUBTRACTOR

State	Input		Output	
	X	Y	B	D
1	0	0	0	0
2	0	1	1	1
3	1	0	0	1
4	1	1	0	0

At the proposed half-subtractor X and Y are the inputs and B and D are the outputs (Figure 2a). Four nonlinear resonant rings are required for connecting inputs to output ports. R#1, R#2, R#3, and R#4 are the nonlinear ring resonators (NRRs) that were implemented via doped-glass made bars inside the resonator (figure 2b). For the doped glass, n=1.4 and $N2=10^{-14}$ m^2/W are used. Different radii was used for the nonlinear bars inside the resonant rings to make different switching thresholds for coupling operation.

R#1 and R#2 were placed between W1 and W2 and W3, respectively and the radii of their nonlinear bars is 126 nm. They couple the light from W1 into W2 and W3, if inside W1, we have $I<10$ $W/\mu m^2$. R#3 is placed between W4 and W5, the radii of nonlinear bars for R#3 is equal to 130 nm. If inside W4, I=7 $W/\mu m^2$, it couples a very small portion of the waves from W4 into W5. Finally, R#4 is placed between W6 and W7 in which the radii of nonlinear bars is 133 nm. This ring couples the waves from W6 into W7, if inside W6 we have $I<3$ $W/\mu m^2$. The switching thresholds of R#1, R#2, R#3, and R#4 are 10, 10, 7, and 3, respectively. Tuning of the thresholds was done by scanning the radii of nonlinear bars with a step of 1nm.

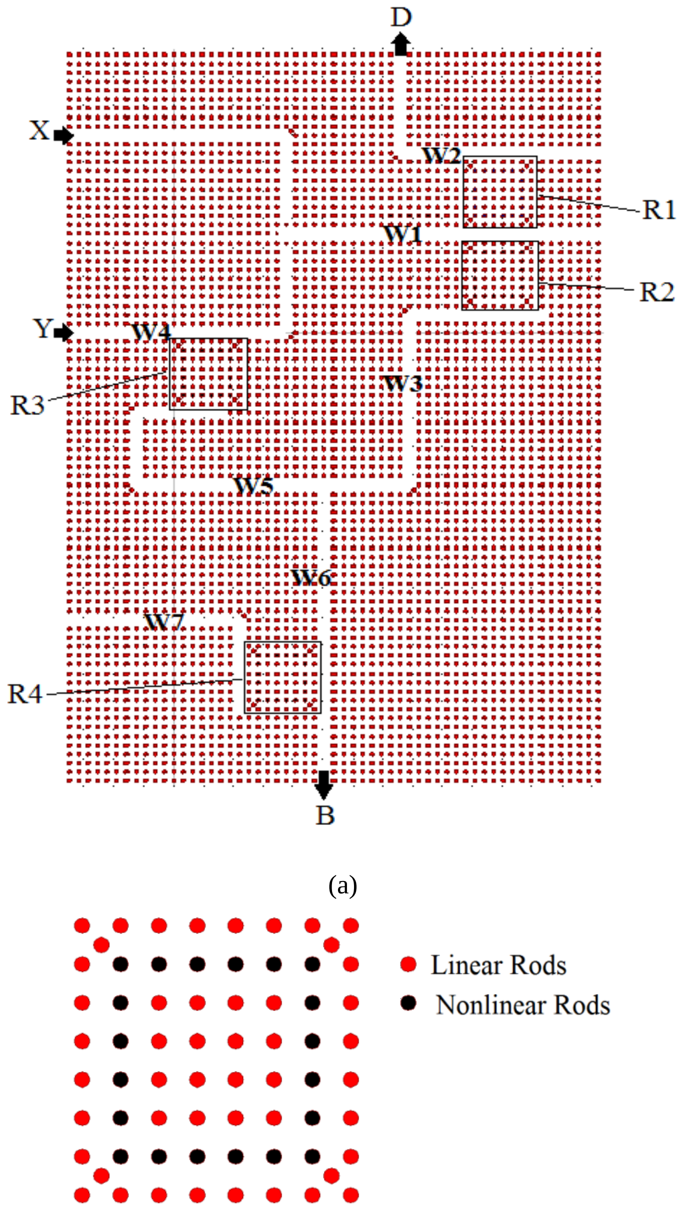


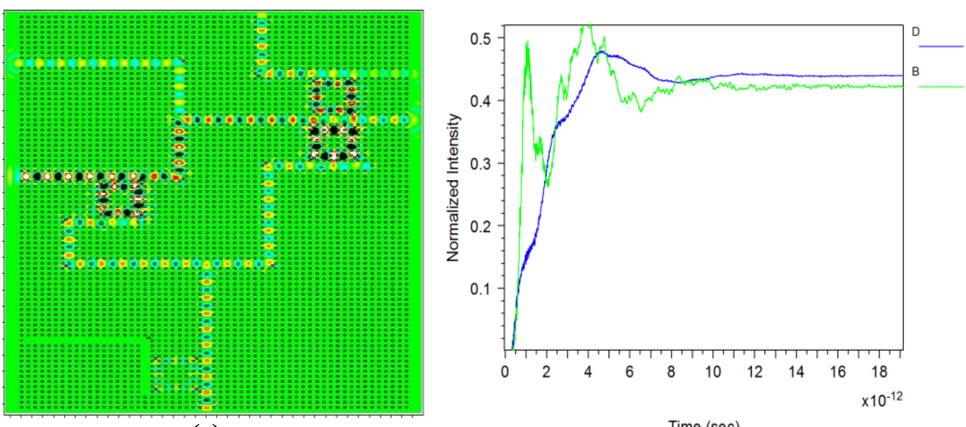
Fig. 2. (a) The OHS structure, (b) the resonant ring.

3. SIMULATION AND RESULTS

The simulations were done using λ=1550 nm and I=7 W/μm^2 respectively. To calculate the components of Maxwell's equation, the perfect match layer (PML) is assumed [47]. Concerning the used radii and wavelength, the unit cell with a length of 1nm is chosen. The time domain is discretized by the step of 1as [48]. To evaluation of the circuit, four states X=Y=0, X=0,Y=1, X=1,Y=0, and X=Y=1 are simulated for X-Y subtraction as the following:

State 1: If both inputs are inactive, due to lack of optical waves both D and B will be inactive.

State 2: For X=0 and Y=1, R#3 couples a small portion of the input signal into W5, the rest of the light travel toward R#1 and R#2. They couple the light from W1 into W2 and W3, respectively. One part of the light is guided toward D (figure 3a). The other part enters W3 and travels toward W5 and W6. These waves are combined with ones coming from R#3 and travel toward R#4. The intensity is more than 3 W/μm^2 so R#4 does not couple them into W7. So the light reaches B. The result of the time analysis corresponding to this state is shown in figure 3b. Based on this figure, the normalized intensities (NI) at D and B are equal to 44% and 42%, respectively. Also, the rise time for D and B are 3.5 ps and 2.5 ps, respectively.

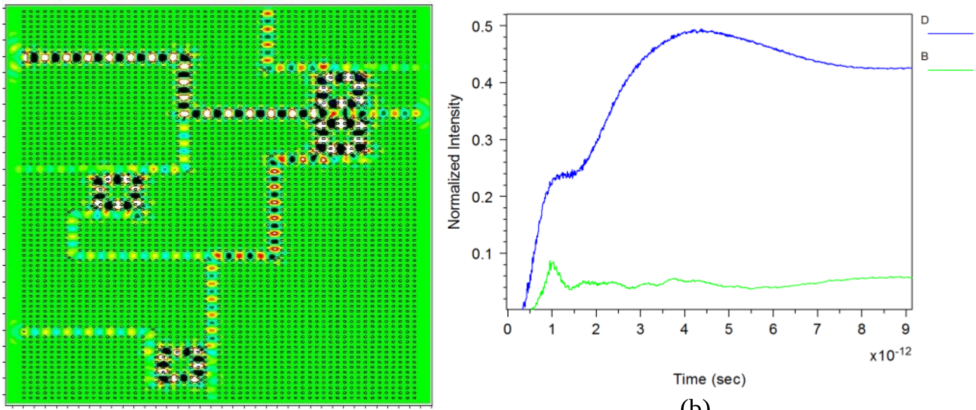


(a)

(b)

Fig. 3. (a) The light guiding inside the circuit, (b) the calculated timing diagram for X=0, Y=1.

State 3: When X =1 and Y =0, the value of optical intensity inside W1 is around 7 W/µm^2, therefore R#1 and R#2 couple the light from W1 into W2 and W3, respectively. R#1 and R#2 act as the power splitters and splits the light into two portions. One portion of the light goes to D and activates it. The other portion enters W3 and travels toward W5 and W6. A small portion of the light with optical intensity less than 3 W/µm^2 reaches R#4 so it couples waves into W7. Therefore, B is inactive (figure 4a). The NI at D and B are 43% and 6%, respectively. Also, the t_r for D and B is around 2.5 ps and 1 ps, respectively (figure 4b).



(a) (b)

Fig. 4. (a) The optical guiding and (b) the timing diagram of the circuit for X=1, Y=0.

State 4: When X=Y=1, R#3 couples a small portion of the incoming light into W4, the rest travel toward W1 where they are combined with the light coming from X (figure 5a). So, I>10 W/µm^2, and R#1 and R#2 do not couple the waves into W2 and W3. Therefore, no light reaches D, as a result, it is inactive. The light that are coupled into W5 travel toward W3 and W6. Due to the low intensity of these waves, R#4 couples them into W7 and no light reach B port. As a result, B is inactive too. The NI at D and B ports are 3% and 4%, respectively. Also, t_r for D and B ports are around 1.4 ps.

The NI at output ports was calculated for multiple radii inside the resonant rings (figure 6). In this way, deviation from the defined values was swept for -5 nm to +5 nm, and the steady-state values of the NI at ports B and D were simulated for states 2, 3, and 4. One can see that the margin of logic 1 was decreased to 0.317 and 0.291 for ports B and D, respectively. Also, the margin of logic 0 was changed to 0.079 for port B and 0.057 for port D.

Figures 3, 4, and 5 demonstrate the correct operation of PC-based HS. In comparison with the previous works [42,45-46] the presented device uses equal power at input ports and results in more possibility for coupling with other devices (table II).

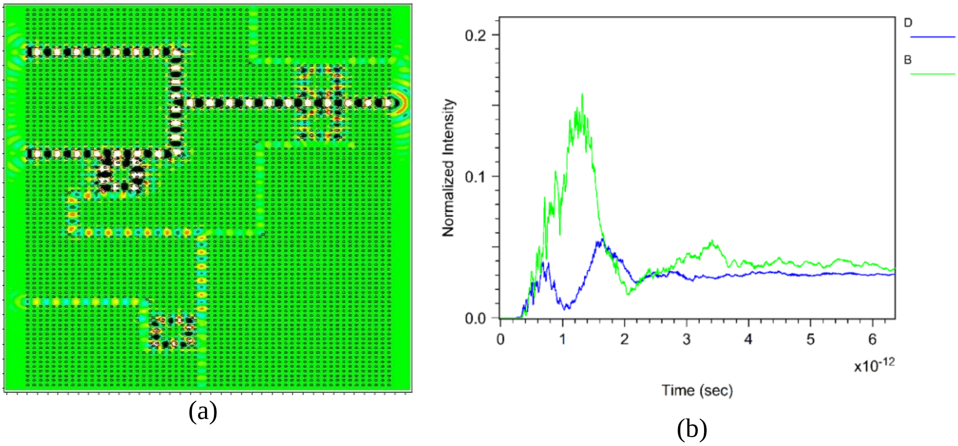


Fig. 5. (a) Guiding the incoming waves from X and Y ports, (b) the calculated timing diagram.

In this work, every input bit is assigned to only one port while applied to two ports for other works [43-45]. Although Moradi [43] and Parandin et al. [42] reported less rise time than the proposed work, the small radii in their structures are the main challenges for fabrication. Based on these issues, it seems that an improvement has been obtained in this research for PC-based half-subtractor. According to some reports [49-58], fabrication of the bars with a radius of 45 nm has been done

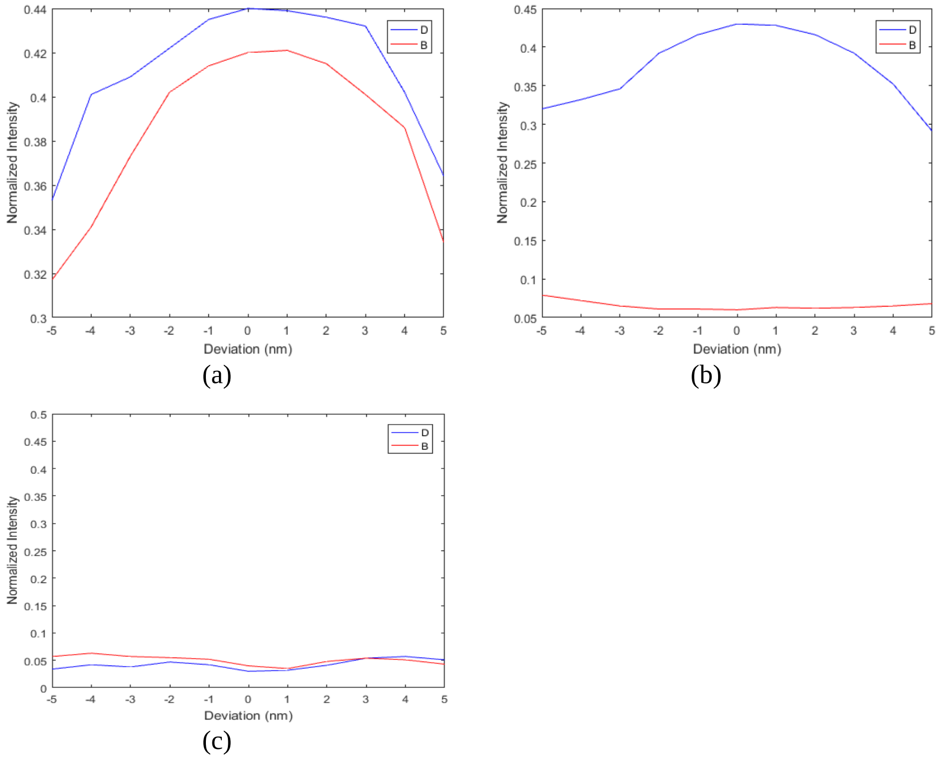


Fig. 6. The NI at output ports for deviation of radii from the defined values, (a) state 2 (X=0,Y=1), (b) state 3 (X=1,Y=0), (c) state 4 (X=Y=1).

Table II

COMPARING THE CHARACTERISTICS OF THE PRESENTED HS WITH PREVIOUS WORKS

Work	Rise time (ps)	Number of input ports	The smallest radii (nm)	Phase shift/ Inequal power
[45]	2	4	108	Yes
[44]	1	4	96	No
[43]	3	4	63	No
[46]	1.5	2	35	Yes
[42]	0.1	2	31	Yes
This work	3.5	2	126	No

CONCLUSION

An OHS circuit was designed using NRRs. Four rings with different switching thresholds were used for this purpose. No extra input port was used for designing the device. Both input ports have the same optical intensities. As shown by the simulations, t_r is 3.5 ps. Also, C_r is 8.45 dB.

REFERENCES

[1] S. John. *Strong localization of photons in certain disordered dielectric superlattices*. Phys. Rev. Lett., 58(23) (1987, June) 2486–2489. Available: https://doi.org/10.1103/PhysRevLett.58.2486

[2] E. Yablonovitch. *Inhibited Spontaneous Emission in Solid-State Physics and Electronics*. Phys. Rev. Lett., 58(20) (1987, May) 2059–2062. Available: https://doi.org/10.1103/PhysRevLett.58.2059

[3] S. M. Mirjalili and S. Z. Mirjalili. *Issues when designing hypoellipse photonic crystal waveguides*. Infrared Phys. Technol., 69 (2015, Mar.) 62–67. Available: https://doi.org/10.1016/j.infrared.2015.01.003

[4] S M. Mirjalili and S. Z. Mirjalili. *Asymmetric Oval-Shaped-Hole Photonic Crystal Waveguide Design by Artificial Intelligence Optimizers.* IEEE J. Sel. Top. Quantum Electron., 22(2) (2016, Mar.) 258–264. Available: https://doi.org/10.1109/JSTQE.2015.2469760

[5] R. Massoudi, M. Najjar, F. Mehdizadeh, and V. Janyani. *Investigation of resonant mode sensitivity in PhC based ring resonators*. Opt. Quantum Electron., 51(3) (2019, March) 87. Available: https://doi.org/10.1007/s11082-019-1793-0

[6] H. Alipour-Banaei and F. Mehdizadeh. *High sensitive photonic crystal ring resonator structure applicable for optical integrated circuits*. Photonic Netw. Commun., 33(2) (2016, April) 152–158. Available: https://doi.org/10.1007/s11107-016-0625-4

[7] M. Youcef Mahmoud, G. Bassou, A. Taalbi, and Z. M. Chekroun. *Optical channel drop filters based on photonic crystal ring resonators.* Opt. Commun., 285(3) (2012, Feb.) 368–372. Available: https://doi.org/10.1016/j.optcom.2011.09.068

[8] A. Taalbi, G. Bassou, and M. Youcef Mahmoud. *New design of channel drop filters based on photonic crystal ring resonators.* Opt. - Int. J. Light

Electron Opt., 124(9) (2013, May) 824–827. Available: https://doi.org/10.1016/J.IJLEO.2012.01.045

[9] M. Youcef Mahmoud, G. Bassou, and A. Taalbi. *A new optical add–drop filter based on two-dimensional photonic crystal ring resonator.* Opt. - Int. J. Light Electron Opt., 124(17) (2013, Sep.) 2864–2867. Available: https://doi.org/10.1016/j.ijleo.2012.08.072

[10] V. Fallahi and M. Seifouri, *Novel structure of optical add/drop filters and multi-channel filter based on photonic crystal for using in optical telecommunication devices*. J. Optoelectron. Nano Struc., 4(2) (2019) 53-68. Available: http://jopn.miau.ac.ir/article_3478.html

[11] V. Fallahi and M. Seifouri, *Novel Four-Channel All Optical Demultiplexer Based on Square PhCRR for Using WDM Applications*. J. Optoelectron. Nano Struc., 3(4) (2018) 59-70. Available: http://jopn.miau.ac.ir/article_3262.html

[12] Z. Zare, A. Gharaati, *Investigation of thermal tunable nano metallic photonic crystal filter with mirror symmetry*. J. Optoelectron. Nano Struc., 3 (3) (2018) 27-36. Available: jopn.miau.ac.ir/article_3043.html

[13] E. Rafiee and F. Emami, *Design and Analysis of a Novel Hexagonal Shaped Channel Drop Filter Based on Two-Dimensional Photonic Crystals*. J. Optoelectron. Nano Struc., 1(2) (2016) 39-46. Available: http://jopn.miau.ac.ir/article_2047.html

[14] R. Talebzadeh, M. Soroosh, Y S. Kavian, and F. Mehdizadeh. *All-optical 6- and 8-channel demultiplexers based on photonic crystal multilayer ring resonators in Si/C rods.* Photonic Netw. Commun., 34(2) (2017, Feb.) 248-57. Available: https://doi.org/10.1007/s11107-017-0688-x

[15] R. Talebzadeh, M. Soroosh, and F. Mehdizadeh. *Improved low channel spacing high quality factor four-channel demultiplexer based on photonic crystal ring resonators.* Opt. Appl., XLVI(4) (2016, Dec.) 553–564. Available: https://doi.org/10.5277/oa160404

[16] R. Talebzadeh, M. Soroosh, and T. Daghooghi. *A 4-Channel Demultiplexer Based on 2D Photonic Crystal Using Line Defect Resonant Cavity*. IETE J. Res., 62(6) (2016, Nov.) 866–872.

Available: https://doi.org/10.1080/03772063.2016.1217175

[17] R. Talebzadeh, M. Soroosh, Y S. Kavian, and F. Mehdizadeh. *Eight-channel all-optical demultiplexer based on photonic crystal resonant*

cavities. Opt. Int. J. Light Electron Opt., 140 (2017, July) 331–337. Available: https://doi.org/10.1016/j.ijleo.2017.04.075

[18] F. Mehdizadeh, H. Alipour-Banaei, and S. Serajmohammadi. *Design and simulation of all optical decoder based on nonlinear PhCRRs*. Opt. - Int. J. Light Electron Opt., 156 (2018, Mar.) 701–706. Available: https://doi.org/10.1016/j.ijleo.2017.12.011

[19] S. Khosravi and M. Zavvari. *Design and analysis of integrated all-optical 2 × 4 decoder based on 2D photonic crystals.* Photonic Netw. Commun., 35(1) (2017, July) 122–128.

Available: https://doi.org/10.1007/s11107-017-0724-x

[20] T. Daghooghi, M. Soroosh, and K. Ansari-Asl. *Ultra-fast all-optical decoder based on nonlinear photonic crystal ring resonators.* Appl. Opt., 57(9) (2018, March) 2250–2257.

Available: https://doi.org/10.1364/AO.57.002250

[21] S. Salimzadeh and H. Alipour-Banaei. *A novel proposal for all optical 3 to 8 decoder based on nonlinear ring resonators*. J. Mod. Opt. [Online]. 65(17) (2018, June) 2017–2024.

Available: https://doi.org/10.1080/09500340.2018.1489077

[22] A. Salimzadeh and H. Alipour-Banaei. *An all optical 8 to 3 encoder based on photonic crystal OR-gate ring resonators.* Opt. Commun., 410 (2018, March) 793–798.

Available: https://doi.org/10.1016/j.optcom.2017.11.036

[23] S. Gholamnejad and M. Zavvari. *Design and analysis of all-optical 4--2 binary encoder based on photonic crystal*. Opt. Quantum Electron., 49(9) (2017, Aug.) 302.

Available: https://doi.org/10.1007/s11082-017-1144-y

[24] S. Serajmohammadi, H. Alipour-Banaei, and F. Mehdizadeh. *Proposal for realizing an all-optical half adder based on photonic crystals*. Appl. Opt., 57(7) (2018) 1617-1621.

Available: https://doi.org/10.1364/AO.57.001617

[25] A. Rahmani and F. Mehdizadeh. *Application of nonlinear PhCRRs in realizing all optical half-adder.* Opt. Quantum Electron. [Online]. 50(1) (2017, Dec.) 30. Available https://doi.org/10.1007/s11082-017-1301-3

[26] M. Neisy, M. Soroosh, and K. Ansari-Asl. *All optical half adder based on photonic crystal resonant cavities*. Photonic Netw. Commun., 35(2) (2018. April) 245–250.

Available: https://doi.org/10.1007/s11107-017-0736-6

[27] M. M. Karkhanehchi, F. Parandin, and A. Zahedi. *Design of an all optical half-adder based on 2D photonic crystals*. Photonic Netw. Commun., 33(2) (2017, april) 159–165.

Available https://doi.org/10.1007/s11107-016-0629-0

[28] A. Andalib. *A novel proposal for all-optical Galois field adder based on photonic crystals*. Photonic Netw. Commun., 35(3) (2018, Jan.) 392–396. Available: https://doi.org/10.1007/s11107-017-0756-2

[29] S. Serajmohammadi, H. Alipour-Banaei, and F. Mehdizadeh. *A novel proposal for all optical 1-bit comparator using nonlinear PhCRRs.* Photonics Nanostructures - Fundam. Appl. 34. (2019, May) 19–23. Available: https://doi.org/10.1016/j.photonics.2019.01.002

[30] A. Surendar, M. Asghari, and F. Mehdizadeh. *A novel proposal for all-optical 1-bit comparator using nonlinear PhCRRs.* Photonic Netw. Commun., 38(2) (2019, Oct.) 244-249.

Available: https://doi.org/10.1007/s11107-019-00853-z

[31] L. Zhu, F. Mehdizadeh, and R. Talebzadeh. *Application of photonic-crystal-based nonlinear ring resonators for realizing an all-optical comparator.* Appl. Opt., 58(30) (2019, Oct.) 8316–8321.

Available: https://doi.org/10.1364/AO.58.008316

[32] SMH. Jalali, M. Soroosh and G. Akbarizadeh . *Ultra-fast 1-bit comparator using nonlinear photoniccrystal based ring resonators*, J. Optoelectron. Nano Struc., 4(3) (2019) 59-72. Available: http://jopn.miau.ac.ir/article_3620.html

[33] S. S. Zamanian-Dehkordi, M. Soroosh, and G. Akbarizadeh. *An ultra-fast all-optical RS flip-flop based on nonlinear photonic crystal structures.* Opt. Rev., 25(4) (2018.Aug.) 523-531.

Available: https://doi.org/10.1007/s10043-018-0443-2

[34] A. Abbasi, M. Noshad, R. Ranjbar, and R. Kheradmand. *Ultra compact and fast All Optical Flip Flop design in photonic crystal platform.* Opt. Commun., 285(24) (2012, Aug.) 5073–5078.

Available: https://doi.org/10.1016/j.optcom.2012.06.095

[35] T. Zhao, M. Asghari, and F. Mehdizadeh. *An All-Optical Digital 2-to-1 Multiplexer Using Photonic Crystal-Based Nonlinear Ring Resonators*. J. Electron. Mater., 48(4) (2019, Jan.) 2482-2486. Available: https://doi.org/10.1007/s11664-019-06947-8

[36] F. Mehdizadeh, M. Soroosh, H. Alipour-Banaei, and E. Farshidi. *A Novel Proposal for All Optical Analog-to-Digital Converter Based on Photonic Crystal Structures.* IEEE Photonics J., 9(2) (2017, april) 1–11. Available: https://doi.org/10.1109/JPHOT.2017.2690362

[37] F. Mehdizadeh, M. Soroosh, H. Alipour-Banaei, and E. Farshidi. *All optical 2-bit analog to digital converter using photonic crystal based cavities.* Opt. Quantum Electron., 49(1) (2017, Jan.) 38.

Available: https://doi: 10.1007/s11082-016-0880-8

[38] F. Mehdizadeh, M. Soroosh, H. Alipour-Banaei H, and E. Farshidi. *Ultra-fast analog-to-digital converter based on a nonlinear triplexer and an optical coder with a photonic crystal structure*. Appl. Opt., 56(7) (2017, Feb.) 1799–1806. Available: https://doi.org/10.1364/AO.56.001799

[39] S. Indira Gandhi and T. Sridarshini. *Design of photonic crystal based optical digital to analog converters.* Laser Phys., 29(4) (2019, March) 046206. Available: https://doi.org/10.1088/1555-6611/ab05d1

[40] D. Jafari, T. Nurmohammadi, M. J. Asadi, and K. Abbasian. *All-optical analog-to-digital converter based on Kerr effect in photonic crystal.* Opt. Laser Technol., 101 (2018, May) 138–143.

Available: https://doi.org/10.1016/j.optlastec.2017.11.007

[41] A. Tavousi, M. A. Mansouri-Birjandi, and M. Saffari. *Successive approximation-like 4-bit full-optical analog-to-digital converter based on Kerr-like nonlinear photonic crystal ring resonators*. Phys. E Low- dimens. Syst. Nanostruct83 (2016, Sep.) 101-106.

Available: https://doi.org/10.1016/j.physe.2016.04.007

[42] F. Parandin, M R. Malmir, and M. Naseri. *All-optical half-subtractor with low-time delay based on two-dimensional photonic crystals.* Superlattices Microstruct., 109 (2017, Sep.) 437–441.

Available: https://doi.org/10.1016/j.spmi.2017.05.030

[43] R. Moradi. *All optical half subtractor using photonic crystal based nonlinear ring resonators*. Opt. Quantum Electron., 51(4) (2019,April) 119. Available: https://doi.org/10.1007/s11082-019-1831-y

[44] A. Askarian, G. Akbarizadeh, and M. Fartash. *A novel proposal for all optical half-subtractor based on photonic crystals*. Opt. Quantum Electron., 51(8) (2019, July) 264. Available: https://doi.org/10.1007/s11082-019-1978-6

[45] A. Askarian, G. Akbarizadeh, and M. Fartash. *All-optical half-subtractor based on photonic crystals.* Appl. Opt., 58(22) (2019, Aug.) 5931-5935. Available: https://doi.org/10.1364/AO.58.005931

[46] N. Namdari and R. Talebzadeh. *Simple and compact optical half subtractor based on photonic crystal resonant cavities in silicon rods*. Applied Optics., 59(1) (2020, Jan.) 165-170.

Available: https://doi.org/10.1364/AO.59.000165.

[47] J. P. Berenger. *A perfectly matched layer for the absorption of electromagnetic waves. J. Comput. phys.* [Online]. 114(2) (1994, Oct.) 185-200. Available: https://doi.org/10.1006/jcph.1994.1159

[48] A. C. Cangellaris. *Numerical stability and numerical dispersion of a compact 2-D/FDTD method used for the dispersion analysis of waveguides.* IEEE Microw. Guided Wave Lett. [Online]. 3(1) (1993, Jan.) 3-5. Available: https://doi.org/10.1109/75.180672

[49] D. Lowell, S. Hassan, O. Sale, M. Adewole, N. Hurley, U. Philipose, B. Chen, and Y. Lin. *Holographic fabrication of graded photonic super-quasi-crystals with multiple-level gradients.* Applied Optics. [Online]. 57(22) (2018, Aug.) 6598-6604. Available: https://doi.org/10.1364/AO.57.006598

[50] L. Pang, W. Nakagawa, and Y. Fainman. *Fabrication of two-dimensional photonic crystals with controlled defects by use of multiple exposures and direct write.* Applied Optics. [Online]. 42(27) (2003, Sep.) 5450-5456. Available: https://doi.org/10.1364/ao.42.005450

[51] M. Campbell, D. N. Sharp,M. T. Harrison, R. G. Denning, and A. J. Turberfield. *Fabrication of photonic crystals for the visible spectrum by holographic lithography*. Nature. [Online]. 404(6773) (2000, Mar.) 53-56. Available: https://doi.org/10.1038/35003523

[52] D. Lowell, S. Hassan, M. Adewole, U. Philipose, B. Chen, and Y. Lin. *Holographic fabrication of graded photonic super-crystals using an*

integrated spatial light modulator and reflective optical element laser projection system. Applied Optics. [Online]. 56(36) (2017, Dec.) 9888-9891. Available https://doi.org/10.1364/AO.56.009888

[53] Y. Liu, S. Liu, and X. Zhang. *Fabrication of three-dimensional photonic crystals with two-beam holographic lithography*. Applied Optics. [Online]. 45(3) (2006, Jan.) 480-483. Available: https://doi.org/10.1364/AO.45.000480

[54] H. M. Ku, C. Y. Huang, and S. Chao. *Fabrication of three-dimensional autocloned photonic crystal on sapphire substrate*. Applied Optics., 50(9) (2011, Mar.) C1-C4.

Available: https://doi.org/10.1364/AO.50.0000C1

[55] O. J. A. Schueller, G. M. Whitesides, J. A. Rogers, M. Meier, and A. Dodabalapur. *Fabrication of photonic crystal lasers by nanomolding of solgel glasses*. Applied Optics., 38(27) (1999, Sep.) 5799-5802. Available: https://doi.org/10.1364/AO.38.005799

[56] J. H. Chen, Y. T. Huang, Y. L. Yang, M. FLu, and J. M. Shieh. *Design, fabrication, and characterization of Si-based ARROW photonic crystal bend waveguides and power splitters.* Applied Optics., 51(24) (2012, Aug.) 5876-5884. Available: https://doi.org/10.1364/AO.51.005876

[57] L. Cui, Y. Zhang, J. Wang, Y. Ren, Y. Song, and L. Jiang. *Ultra Fast Fabrication of Colloidal Photonic Crystals by Spray Coating.* Macromolecular Rapid Communications., 30(8) (2009, April) 598-603. Available: https://doi.org/10.1002/marc.200800694

[58] G. V. Freymann, V. Kitaev, B. V. Lotschz, and G. A. Ozin. *Bottom-up assembly of photonic crystals*. Chem Soc Rev., 42(7) (2013, Mar.) 2528-2554. Available: https://doi.org/10.1039/c2cs35309a