A novel design of fast and compact all-optical full-adder using nonlinear resonant cavities

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Abstract

In this paper, we report a new design of an all-optical full-adder using two nonlinear resonators. The PhC-based full-adder consists of three input ports (A, B, and C for input bits), two nonlinear resonant cavities, several waveguides, and two output ports (for the SUM and CARRY). Eight silicon rods and a nonlinear rod composed of doped glass form each resonant cavity. The well-known plane wave expansion technique is used to calculate the photonic band structure. It shows a wide photonic bandgap in the wavelength range of 1365–2074 nm covering the C and L optical transmission bands. The finite-difference time-domain method is applied to study the light propagation inside the full-adder. Our numerical results demonstrate when the incoming light intensity increases, the nonlinear optical Kerr effect appears and controls the direction of light emitted inside the structure as desired. The maximum time delay and footprint of the proposed full-adder are about 3 ps and 758.5 μm², respectively. Therefore, due to the low time delay and small footprint, the presented design can be used as a basic mathematical operator in the all-optical arithmetic logic unit.

Keywords Full-adder · Photonic crystal · Optical Kerr effect · Resonant cavity

1 Introduction

Ultrafast signal processing is a key advantage of optical devices used in telecommunication systems. Computation and communication functions must be carried out without using electrical signals in the optical domain. Signal processing is an important step in optical system design. All-optical logic gates are crucial for realizing ultrafast signal processing (Rahmani and Mehdizadeh 2018; Saghaei et al. 2017; Sharifi et al. 2016). Full-adder is an optical signal process device used in every fundamental mathematical operator (Cheraghi et al. 2018; Jiang et al. 2015; Liu and Ouyang 2008; Maleki et al. 2020; Sani et al. 2020; Vali-Nasab et al. 2019). A full-adder consists of three input ports and two output...
ports; thus, it can add three binary digits, and two binary digits can be obtained at the output ports called SUM and CARRY. A photonic crystal (PhC) may have one or more photonic band gaps (PBGs) in specific wavelength ranges in one or more directions. This unique property results in light emission in the desired directions by creating defects in the PhC (Alipour-Banaei and Mehdizadeh 2013; Hosseinzadeh Sani et al. 2020a, b; Mehdizadeh et al. 2017b). Thus full-adder design using PhC is recommended. PhCs ring resonators (PCRRs) provide excellent performance for designing and realizing multiple optical devices with a minimal area and low manufacturing cost. Thus, they are more popular among designers. A large number of parameters, including the radius of the dielectric rod, the lattice constant, the type of rod arrangement, the dielectric constant, and the PhC unit cells’ position, affect the resonant’s intensity and frequency modes (Biswas et al. 2020; Farmani et al. 2020; Mansouri-Birjandi et al. 2016; Naghizade et al. 2018; Naghizade and Sattari-Esfahan 2017a; Tavousi et al. 2017). By changing every parameter, the blue or red-shift occurs at resonant modes. Every PCRR has a resonant mode, acting as an optical pass-band or stop-band filter. So far, a large number of PhC-based devices such as optical filters (Alipour-Banaei et al. 2014; Foroughifar et al. 2021; Guo et al. 2019; Naghizade and Saghaei 2020a; Rakhshani and Mansouri-Birjandi 2013), logic gates (Andalib and Granpayeh 2009; Hussein et al. 2018; Younis et al. 2014), encoders (Moniem 2016; Naghizade et al. 2018; Naghizade and Khoshshima 2018; Naghizade and Sattari-Esfahan 2020b), comparators (Fakouri-Farid and Andalib 2018; Jile 2020), multiplexers and demultiplexers (Naghizade and Mohammadi 2020; Naghizade and Sattari-Esfahan 2017b), adders and subtractors (Alipour-Banaei and Seif-Dargahi 2017; Gerali et al. 2019; Hosseinzadeh Sani et al. 2020a; Maleki et al. 2021a, b; Moradi 2019; Naghizade and Saghai 2021a, 2020c), registers (Martinez-Dorantes et al. 2017; Pahari and Guchhait 2012), and memories (Alexoudi et al. 2020; Kuramochi et al. 2014; Uda et al. 2018), splitters (Naghizade and Mohammadi 2019; Parandin et al. 2018; Saghaei et al. 2017), analog-to-digital converters (Mehdizadeh et al. 2017c; Naghizade and Saghaei 2021b; Tavousi and Mansouri-Birjandi 2018), optical fibers (Aliie et al. 2020; Diouf et al. 2017; Ghanbari et al. 2017, 2018; Saghaei 2017; Saghaei et al. 2015, 2016a, b), sensors (Alden Mostaan and Saghaei 2021; Kowsari and Saghaei 2018; Tabrizi et al. 2021; Tavakoli et al. 2019), PhC fibers (Diouf et al. 2017; Ebnali-Heidari et al. 2012, 2014; Ghanbari et al. 2019; Kalantari et al. 2018; Raei et al. 2018; Saghaei 2018; Saghaei et al. 2015; Saghaei and Ghanbari 2017; Saghaei and Van 2019), switches (Alipour-Banaei et al. 2015; Chen et al. 2006; Danaie and Kaatuzian 2011; Mehdizadeh et al. 2017a), interferometers (Danaee et al. 2019; Gu et al. 2007; Saghaei et al. 2019), as well as all-optical clocked sequential circuits including flip-flops (Rao et al. 2020; Zamanian-Dehkordi et al. 2018), synchronous and asynchronous counters (Kaur and Kaler 2014; Poustie et al. 2000) have been designed and fabricated. New functionality was created using high nonlinear dielectric rods in the resonator, and switching applications can be achieved. Recently, all-optical half-adders and full-adders were designed using linear and nonlinear properties of PhCs (Moradi et al. 2018; Neisy et al. 2018; Swarnakar et al. 2018). Neisy et al. (2018) reported an all-optical half adder based on two nonlinear resonant cavities. These resonant cavities have different resonant modes; therefore, their coupling operations depend on the incoming light intensity. Alipour-Banaei and Seif-Dargahi (2017) proposed an all-optical one-bit full-adder based on PCRRs. Their proposed structure was composed of two cascaded half-adders. Cheraghi et al. (2018) presented an all-optical full-adder using four PCRRs. The worst cases for logics 0 and 1 were 3% and 53% for SUM port, and they were 10% and 100% for CARRY port, respectively. The previous works had high input power intensities and roughly low transmission efficiency for the SUM and CARRY ports. Thus we aim to improve these features.
In this paper, we present an all-optical full-adder using two nonlinear resonant cavities. The plane wave expansion (PWE) and finite-difference time-domain (FDTD) methods are used to analyze the optical behavior of the proposed structure (Johnson and Joannopoulos 2001; Qiu 2002). Due to time and memory limitations, an effective refractive index method is used to reduce the 3D into 2D simulations with perfect accuracy. The paper is organized as follows. The full-adder’s physical structure and the numerical results achieved by the PWE method are presented in Sect. 2. Section 3 describes the light propagation inside the full-adder using the numerical FDTD method, and the paper is closed by the conclusion in Sect. 4.

2 Physical structure

Figure 1 shows the schematic view of a typical full-adder and its truth table. We observe that a full-adder has been designed by combining two optical half-adders and an OR logic gate. Each half-adder consists of two input ports of A and B, and two output ports of S and C that S and C stand for SUM and CARRY, respectively.

The first half-adder output of S has been connected to the first input port of the second half-adder. C ports of optical half-adders are the OR gate’s inputs and form the CARRY of the final full adder and the S port of the second half-adder is also the SUM port of the full-adder. Besides, A, B, and Cin are the three input ports of the full-adder.

In this study, we aim to design an all-optical full-adder in a rod-based PhC. The fundamental PhC structure used to design the proposed structure consists of dielectric rods with hexagonal lattice geometry.

The refractive index and radius of dielectric rods are assumed to be 3.46 and 0.21a, where a is the lattice constant of the PhC structure. Using the PWE method, the photonic band diagram of the fundamental structure has been calculated and shown in Fig. 2. It shows a wide PBG region at $0.27 < a/\lambda < 0.41$ for TM polarization mode, which is equal to $1365 \text{ nm} < \lambda < 2074 \text{ nm}$ for $a = 560 \text{ nm}$. This bandwidth covers C and L optical transmission bands. The lowest optical fiber loss is in the C-band (1530–1565 nm) and is generally used in many transmission applications. The L-band (1565–1625 nm) is the second

![Fig. 1](image)

**Fig. 1** Illustration of a the full-adder circuit consisting of two half-adders and an OR logic gate, three input ports of A, B, and Cin, and two output ports of SUM and CARRY, b the truth table of full-adder for all states
lowest-loss wavelength band and is a popular choice when the use of the C-band is not sufficient to meet the bandwidth demand.

Figure 3 shows that the resonator used in the proposed full-adder consists of three waveguides (one input and two output waveguides) and two cavities. As seen in the figure, eight silicon rods (shown in red) and a nonlinear rod composed of doped glass (shown in blue in the top-right view with a radius of 128 nm and shown in green in the bottom-right view with a radius of 118 nm) form each cavity. The doped glass has a linear refractive index of 1.4 and a nonlinear optical Kerr coefficient of about $10^{-14}$ m$^2$/W.

An optical beam is launched in the input waveguide and dropped to one of the nonlinear cavities’ output ports depending on the input power. The time-domain light propagation inside the resonator for two different optical powers are shown in Fig. 4a, b. As shown in the figure, when an optical intensity of 10 mW/$\mu$m$^2$ enters the input waveguide, it exits the first output port ($O_1$) by creating a resonant mode in the first cavity (top) because the resonance mode is equal to the center wavelength of the input signal for this amount of optical power. When the optical intensity is 20 mW/$\mu$m$^2$, resonant mode occurs at the second cavity (bottom), and the optical beam goes out from the second output port ($O_2$).

Fig. 3 The schematic view of PhC resonator consisting of three waveguides (one input and two output waveguides) and two resonant cavities
Figure 5 shows the proposed full-adder consisting of ten waveguides and four resonant cavities (RCs) at suitable places and directions inside the fundamental PhC structure. The first half adder is formed by combining W1, W2, and W3 waveguides with RCs1. The first half adder’s S and C ports are placed at the end of W4 and W5 ports, respectively. Also, W5, W6, W7, and RCs2 form the second half-adder. The outputs of W10 and W8 are its S and C ports, respectively. W4, W8, and W9 form the OR gate, and W9 works as the CARRY port of the proposed full-adder. Also, the right side of the W10 works as the SUM output port. A, B, and C are defined as the input ports of the proposed full-adder. Both RCs work with the same propagating method when the optical intensity is 10 mW/μm², the right-hand cavity (the one with blue rod) couples the optical beam into its output waveguide, however for the optical intensity of about 20 mW/μm², another cavity (the cavity with green rod) couples the optical beam to its output.

3 Simulation results

We employed the FDTD method to analyze and simulate the light propagation inside the proposed full-adder shown in Fig. 5, which contains three input ports. Therefore, according to the computation principle, we have $2^3 (2^N, N$ is the number of input ports) different
input states. The optical intensity of the input ports is equal to 10 mW/μm². The simulation results are discussed as follows for all states of the input ports.

**Case #1** In this state, all the input ports are OFF (i.e., A = 0, B = 0, and C = 0); thus, there is no optical signal in the structure, and both output ports are OFF, and finally, the amounts of SUM and CARRY will be zero.

**Case #2** When A = 1, B = 0, and C = 0, the optical signal coming from input port A, travels close to RCs1 through W1 and W3. Since the optical intensity is equal to 10 mW/μm², the optical signal will be dropped into W5 and W7, and it is dropped into W10 using RCs2 and travels toward the full-adder’s SUM port, thus, SUM = 1 and CARRY = 0, the light propagation inside the proposed full-adder is shown in Fig. 6a. Figure 6b shows that in this case, the normalized powers at SUM and CARRY output ports are more than 90% and less than 2%, respectively. Also, the time delay is about 3.5 ps.

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**Fig. 5** The schematic view the proposed all-optical full-adder consisting of three input ports (for three input digits), ten waveguides, four resonant cavities, and two output ports (for SUM and CARRY)

**Fig. 6** Illustration of a light propagation and b output powers of the proposed full-adder for Case #2
Case #3 When A = 0, B = 1, and C = 0, the optical signal coming from input port B, travels close to RCs1 through W2 and W3. Since the optical intensity is equal to 10 W/μm², the optical signal will be dropped into W5 and propagates inside W7, it is dropped into W10 using RCs2 and travels toward the SUM output port. Therefore, we have SUM = 1 and CARRY = 0. The light propagation inside the structure is shown in Fig. 7a. Figure 7b shows that in this case, the normalized powers at SUM and CARRY are more than 90% and less than 2%, respectively. Also, the time delay is about 3.5 ps.

Case #4 When A = 0, B = 0, and C = 1, the optical signal coming from input port C, travels close to RCs2 through W6 and W7. Since the optical intensity is 10 mW/μm², the optical signal will be dropped into W10 and travels toward the SUM output port; thus, we have SUM = 1 and CARRY = 0. The light propagation inside the structure is shown in Fig. 8a. Figure 8b shows that in this case, the normalized powers at SUM and CARRY are more than 88% and less than 1%, respectively. Also, the time delay is about 3 ps.

Case #5 When A = 1, B = 1, and C = 0, the optical signals coming from input ports A (in W1), and B (in W2) are combined at W3 and form a resultant signal with an optical intensity of 20 mW/μm². Therefore, RCs1 drops the optical signal into W4 and it
travels toward the CARRY output port through W9. The light propagation inside the structure is shown in Fig. 9a. It demonstrates that there is no optical beam in W10. Thus, this case has $\text{SUM} = 0$ and $\text{CARRY} = 1$. Figure 9b shows that $\text{SUM}$ and CARRY’s normalized powers are less than 5% and more than 160%, respectively. Also, the rise time and the steady-state time are about 0.3 ps and 3 ps, respectively.

**Case #6** When $A = 1$, $B = 0$, and $C = 1$, the optical beam coming from input port A (in W1), travels close to RCs1 through W3. since the optical intensity is 10 mW/μm², a resonant mode occurs, and the optical signal is dropped into W5. The optical beam coming from input port C with an optical intensity of 10 mW/μm² propagates in W6 and is added to the signal coming from W5 at the input of W7. Then the resultant signal is formed with an optical intensity of 20 mW/μm². This new signal propagates inside W7. Since the optical intensity in this waveguide is 20 mW/μm², the RCs2 drops the optical beam from W7 into W8, and it travels toward the CARRY output port through W9. Thus, in this case, we will have $\text{SUM} = 0$ and $\text{CARRY} = 1$. The light propagation inside the structure is shown in Fig. 10a. Figure 10b shows that for this case, the normalized powers at $\text{SUM}$ and CARRY are less than 2% and more than 125%, respectively. Also, the steady-state time is about 3 ps.
Case #7 When \( A = 0, B = 1, \) and \( C = 1, \) the optical beam coming from input port \( B \) (in W2), propagates in the vicinity of the RCs1 through W3. Then the optical signal is dropped into W5 because the optical intensity is 10 mW/\( \mu m^2 \). Similar to Case #6, the optical beam coming from input port \( C \) propagates in W6. It is added to the signal coming from W5 at the input of W7 and forms an optical beam with an intensity of 20 mW/\( \mu m^2 \). This new signal propagates inside W7. Since the optical intensity in this waveguide is 20 mW/\( \mu m^2 \), the RCs2 drops the optical beam from W7 into W8 and it travels toward the CARRY output port through W9. Thus we have SUM = 0 and CARRY = 1. The light propagation inside the structure is shown in Fig. 11a. Figure 11b shows that in this case, the normalized powers at SUM and CARRY are less than 2% and more than 125%, respectively. Also, the steady-state time is about 3 ps.

Case #8 When \( A = 1, B = 1, \) and \( C = 1, \) the optical signals coming from input ports A (in W1), and B (in W2) are combined at W3 and form a resultant signal with an optical intensity of 20 mW/\( \mu m^2 \). Therefore, RCs1 drops the optical signal into W4, and it travels toward the CARRY output port through W9. The optical signal coming from input port C, travels close to RCs2 through W6 and W7. Since the optical intensity is 10 mW/\( \mu m^2 \), the optical signal will be dropped into W10 and travels toward the SUM output port; thus, we have SUM = 1 and CARRY = 1.

The light propagation inside the structure is shown in Fig. 12a. Figure 12b shows that in this case, the normalized powers at SUM and CARRY are about 90% and 160%, respectively. Also, the steady-state time is about 3 ps.

The numerical results of all eight input states are SUMmarized in Table 1, and it shows that the proposed structure is acting as an all-optical full-adder. The results of this study were compared with other published papers in Table 2. It shows the input intensity, the steady-state time, and minimum output powers for logics 0 and 1 and confirms the superiority of our structure’s results compared to previously reported works.

In order to determine the margins of logics 0 and 1, the worst cases are considered (Maleki et al. 2021a). The contrast ratio is defined as \( 10\log(M_1/M_0) \) where \( M_1 \) and \( M_0 \) are the margins of logics 1 and 0, respectively. According to Table 1, these ratios for SUM (\( M_0 = 5 \) and \( M_1 = 90 \)) and CARRY (\( M_0 = 2 \) and \( M_1 = 125 \)) are equal to 12.55 dB and 17.95 dB, respectively.

Fig. 11 Illustration of a light propagation and b output powers of the proposed full-adder for Case #7
4 Conclusion

In summary, we designed a fast and compact all-optical full-adder using several non-linear nanocavities. Eight different states for three input digits were simulated using the
well-known FDTD method assuming PML boundary conditions. The numerical results revealed the proposed full-adder has a maximum steady-state time of about 3 ps. The structure’s total size was equal to 758.5 μm², which was more compact than other works. Furthermore, appropriate power margins for logic zero and one were obtained at 1% and 90%, respectively. As a result, the presented half-adder can be used in optical integrated circuits for high-speed signal processing.

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**Declarations**

**Conflict of interest** The authors have no conflict of interest.

**References**

Alden Mostaan, S.M., Saghaei, H.: A tunable broadband graphene-based metamaterial absorber in the far-infrared region. Opt. Quantum Electron. 53, 96 (2021). https://doi.org/10.1007/s11082-021-02744-y

Alexoudi, T., Kanellos, G.T., Pleros, N.: Optical RAM and integrated optical memories: a survey. Light Sci. Appl. 9, 1–16 (2020). https://doi.org/10.1038/s41377-020-0325-9

Alikee, M., Mozaffari, M.H., Saghaei, H.: Dispersion-flattened photonic quasicrystal optofluidic fiber for telecom C band operation. Photonics Nanostruct. Fundam. Appl. 40, 100797 (2020). https://doi.org/10.1007/journal.2020.100797

Alipour-Banai, H., Meh dizadeh, F.: Bandgap calculation of 2D hexagonal photonic crystal structures based on regression analysis. J. Opt. Commun. 34, 285–293 (2013)

Alipour-Banai, H., Seif-Dargahi, H.: Photonic crystal based 1-bit full-adder optical circuit by using ring resonators in a nonlinear structure. Photonics Nanostruct. Fundam. Appl. 24, 29–34 (2017)

Alipour-Banai, H., Jahanara, M., Meh dizadeh, F.: T-shaped channel drop filter based on photonic crystal ring resonator. Optik (Stuttg) 125, 5348–5351 (2014)

Alipour-Banai, H., Meh dizadeh, F., Serajmohammadi, S., Hassangholizadeh-Kashibian, M.: A 2* 4 all optical decoder switch based on photonic crystal ring resonators. J. Mod. Opt. 62, 430–434 (2015)

Andalib, P., Granpayeh, N.: All-optical ultracompact photonic crystal AND gate based on nonlinear ring resonators. J. Opt. Soc. Am. B. 26, 10 (2009). https://doi.org/10.1364/josab.26.000100

Biswas, U., Rakshit, J.K., Bharti, G.K.: Design of photonic crystal microring resonator based all-optical refractive-index sensor for analyzing different milk constituents. Opt. Quantum Electron. 52, 19 (2020)

Cheraghi, F., Soroosh, M., Akbarizadeh, G.: An ultra-compact all optical full adder based on nonlinear photonic crystal resonant cavities. Superlattices Microstruct. 113, 359–365 (2018). https://doi.org/10.1016/j.spmi.2017.11.017

Danaee, E., Geravand, A., Danaie, M.: Wide-band low cross-talk photonic crystal waveguide intersections using self-collimation phenomenon. Opt. Commun. 431, 216–228 (2019). https://doi.org/10.1016/j.comcom.2018.09.032

Danaie, M., Kaatuzian, H.: Bandwidth improvement for a photonic crystal optical Y-splitter. J. Opt. Soc. Korea 15, 283–288 (2011)

Diouf, M., Salem, A.B., Cherif, R., Saghaei, H., Wague, A.: Super-flat coherent supercontinuum source in As_388S_e 612 chalcogenide photonic crystal fiber with all-normal dispersion engineering at a very low input energy. Appl. Opt. 56, 163-169 (2017). https://doi.org/10.1364/ao.56.00163

Ebnali-Heidari, M., Dehghan, F., Saghaei, H., Koohi-Kamali, F., Moravej-Farshi, M.K.: Dispersion engineering of photonic crystal fibers by means of fluidic infiltration. J. Mod. Opt. 59, 1384–1390 (2012). https://doi.org/10.1080/09500340.2012.715690

Ebnali-Heidari, M., Saghaei, H., Koohi-Kamali, F., Naser Moghadasi, M., Moravej-Farshi, M.K.: Proposal for supercontinuum generation by optofluidic infiltrated photonic crystal fibers. IEEE J. Sel. Top. Quantum Electron. 20, 582-589 (2014). https://doi.org/10.1109/JSTQE.2014.2307313

Fakouri-Farid, V., Andalib, A.: Design and simulation of an all optical photonic crystal-based comparator. Optik (Stuttg) 172, 241–248 (2018). https://doi.org/10.1016/j.ijleo.2018.06.153
Farmani, A., Soroosh, M., Mozaffari, M.H., Daghooghi, T.: Optical nanosensors for cancer and virus detections. In: Nanosensors for Smart Cities. pp. 419–432. Elsevier (2020).

Foroughifar, A., Saghaei, H., Veisi, E.: Design and analysis of a novel four-channel optical filter using ring resonators and line defects in photonic crystal microstructure. Opt. Quant. Electron. (2021). https://doi.org/10.1007/s11082-021-02743-z.

Geraiali, M.R., Hosseini, S.E., Tavakoli, M.B., Shokooh-Saremi, M.: A proposal for an all optical full adder using nonlinear photonic crystal ring resonators. Optik (Stuttg) 199, 163359 (2019).

Ghanbari, A., Kashaniania, A., Sadr, A., Saghaei, H.: Supercontinuum generation for optical coherence tomography using magnesium fluoride photonic crystal fiber. Optik (Stuttg) 140, 545–554 (2017). https://doi.org/10.1016/j.photonics.2017.04.099.

Ghanbari, A., Kashani Nia, A., Sadr, A., Saghaei, H.: A comparative study of multipole and empirical relations methods for effective index and dispersion calculations of silica-based photonic crystal fibers. J. Commun. Eng. 8, 98–109 (2019). https://doi.org/10.22070/jce.2019.4016.1125.

Ghanbari, A., Kashaniania, A., Sadr, A., Saghaei, H.: Supercontinuum generation with femtosecond optical pulse compression in silicon photonic crystal fibers at 2500 nm. Opt. Quantum Electron. 50, 411 (2018). https://doi.org/10.1007/s11082-018-1651-5.

Gu, L., Jiang, W., Chen, X., Wang, L., Chen, R.T.: High speed silicon photonic crystal waveguide modulator for low voltage operation. Appl. Phys. Lett. 90, 71105 (2007). https://doi.org/10.1063/1.2475580.

Guo, Y., Zhang, S., Li, J., Li, S., Cheng, T.: A sensor-compatible polarization filter based on photonic crystal fiber with dual-open-ring channel by surface plasmon resonance. Optik (Stuttg) 193, 162868 (2019). https://doi.org/10.1016/j.ijleo.2019.05.074.

Hosseinazadeh Sani, M., Ghanbari, A., Saghaei, H.: An ultra-narrowband all-optical filter based on the resonant cavities in rod-based photonic crystal microstructure. Opt. Quant. Electron. 52, 295 (2020a). https://doi.org/10.1007/s11082-020-02418-1.

Hosseinazadeh Sani, M., Saghaei, H., Mehranpour, M.A., Asgariyan Tabrizi, A.: A novel all-optical sensor design based on a tunable resonant nanocavity in photonic crystal microstructure applicable in MEMS accelerometers. Photonic Sensors (2020b). https://doi.org/10.1007/s13320-020-00670-0.

Hussein, H.M.E., Ali, T.A., Rafat, N.H.: New designs of a complete set of Photonic Crystals logic gates. Opt. Commun. 411, 175–181 (2018). https://doi.org/10.1016/j.optcom.2017.11.043.

Jiang, Y.C., Liu, S.B., Zhang, H.F., Kong, X.K.: Realization of all optical half-adder based on self-collimated beams by two-dimensional photonic crystals. Opt. Commun. 348, 90–94 (2015). https://doi.org/10.1016/j.optcom.2015.03.011.

Jile, H.: Realization of an all-optical comparator using beam interference inside photonic crystal waveguides. Appl. Opt. 59, 3714 (2020). https://doi.org/10.1364/ao.385744.

Johnson, S., Joannopoulos, J.: Block-iterative frequency-domain methods for Maxwell’s equations in a planewave basis. Opt. Express. 8, 173 (2001). https://doi.org/10.1364/oe.8.000173.

Kalantari, M., Karimkhani, A., Saghaei, H.: Ultra-Wide mid-IR supercontinuum generation in As2S3 photonic crystal fiber by rods filling technique. Optik (Stuttg) 158, 142–151 (2018). https://doi.org/10.1016/j.ijleo.2017.12.014.

Kaur, S., Kaler, R.S.: 5 GHz all-optical binary counter employing SOA-MZIs and an optical NOT gate. J. Opt. (United Kingdom) 16, 35201 (2014). https://doi.org/10.1088/2040-8978/16/3/035201.

Kowsari, A., Saghaei, H.: Resonantly enhanced all-optical switching in microfiber Mach-Zehnder interferometers. Electron. Lett. 54, 229–231 (2018). https://doi.org/10.1049/el.2017.4056.

Kuramochi, E., Nozaki, K., Shinya, A., Takeda, K., Sato, T., Matsuo, S., Taniyama, H., Sumikura, H., Notomi, M.: Large-scale integration of wavelength-addressable all-optical memories on a photonic crystal chip. Nat. Photonics. 8, 474–481 (2014). https://doi.org/10.1038/nphoton.2014.93.

Liu, Q., Ouyang, Z.B.: All-optical half adder based on cross structures in two-dimensional photonic crystals. Guangxi Xuebao/Acta Photonica Sin. 37, 46–50 (2008). https://doi.org/10.1364/oe.16.018992.

Maleki, M.J., Mir, A., Soroosh, M.: Designing an ultra-fast all-optical full-adder based on nonlinear photonic crystal cavities. Quant. Electron. 52, 1–11 (2020).

Maleki, M.J., Mir, A., Soroosh, M.: Design and analysis of a new compact all-optical full-adder based on photonic crystals. Optik (Stuttg) 227, 166107 (2021a). https://doi.org/10.1016/j.ijleo.2020.166107.

Maleki, M.J., Mir, A., Soroosh, M.: Ultra-fast all-optical full-adder based on nonlinear photonic crystal resonant cavities. Photonic Netw. Commun. 41, 93–101 (2021b). https://doi.org/10.1007/s11107-020-00917-5.

Mansouri-Birjandi, M.A., Tavousi, A., Ghahrdan, M.: Full-optical tunable add/drop filter based on nonlinear photonic crystal ring resonators. Photonics Nanostruct. Fundam. Appl. 21, 44–51 (2016). https://doi.org/10.1016/j.photonics.2016.06.002.
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Martinez-Dorantes, M., Alt, W., Gallego, J., Ghosh, S., Ratschbacher, L., Völzke, Y., Meschede, D.: Fast non-destructive parallel readout of neutral atomic registers in optical potentials. Phys. Rev. Lett. 119, 180503 (2017). https://doi.org/10.1103/PhysRevLett.119.180503

Mehdizadeh, F., Alipour-Banaei, H., Serajmohammadi, S.: Study the role of non-linear resonant cavities in photonic crystal-based decoder switches. J. Mod. Opt. 64, 1233–1239 (2017a). https://doi.org/10.1080/09500340.2016.1275854

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 J. 9, 1–11 (2017b). https://doi.org/10.1109/JPHOTO.2017.2690362

Mehdizadeh, F., Soroosh, M., Alipour-Banaei, H., Farshidi, E.: All optical 2-bit analog to digital converter using photonic crystal based cavities. Opt. Quantum Electron. 49, 38 (2017c). https://doi.org/10.1007/s11082-016-0880-8

Moniemi, T.A.: All-optical digital 4 × 2 encoder based on 2D photonic crystal ring resonators. J. Mod. Opt. 63, 735–741 (2016). https://doi.org/10.1080/09500340.2015.1094580

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

Moradi, M., Danaie, M., Orouji, A.A.: Design and analysis of an optical full-adder based on nonlinear photonic crystal ring resonators. Optik (Stuttg) 172, 127–136 (2018)

Naghizade, S., Khoshshima, H.: Low input power an all optical 4×2 encoder based on triangular lattice shape photonic crystal. J. Opt. Commun. 1, 1–8 (2018). https://doi.org/10.1515/joc-2018-0019

Naghizade, S., Mohammadi, S.: Design and engineering of dispersion and loss in photonic crystal fiber 1 × 4 power splitter (PCFPS) based on hole size alteration and optofluidic infiltration. Opt. Quantum Electron. 51, 17 (2019). https://doi.org/10.1007/s11082-018-1731-6

Naghizade, S., Mohammadi, S.: Optical four-channel demultiplexer based on air-bridge structure and graphite-type ring resonators. Photon. Netw. Commun. 40, 40–48 (2020)

Naghizade, S., Saghafi, H.: Tunable graphene-on-insulator band-stop filter at the mid-infrared region. Opt. Quantum Electron. 52, 224 (2020a). https://doi.org/10.1007/s11082-020-02350-4

Naghizade, S., Saghafi, H.: A novel design of all-optical 4 to 2 encoder with multiple defects in silica-based photonic crystal fiber. Optik (Stuttg) 222, 165419 (2020b). https://doi.org/10.1016/j.ijleo.2020.165419

Naghizade, S., Saghafi, H.: A novel design of all-optical half-adder using a linear defect in photonic crystal microstructure. J. Appl. Res. Electr. Eng. 1 (2020c). https://doi.org/10.22055/jaree.2020.34466.1010

Naghizade, S., Saghafi, H.: A novel design of all-optical full-adder using nonlinear X-shaped photonic crystal resonators. Opt. Quantum Electron. 53, 154 (2021)

Naghizade, S., Saghafi, H.: An ultra-fast optical analog-to-digital converter using nonlinear X-shaped photonic crystal ring resonators. Opt. Quantum Electron. 53, 149 (2021)

Naghizade, S., Sattari-Esfahan, S.M.: Loss-less elliptical channel drop filter for WDM applications. J. Opt. Commun. 40, 379–384 (2017). https://doi.org/10.1515/joc-2017-0088

Naghizade, S., Sattari-Esfahan, S.M.: High-performance ultra-compact communication triplexer on silicon-on-insulator photonic crystal structure. Photonic Netw. Commun. 34, 445–450 (2017). https://doi.org/10.1007/s11107-017-0702-3

Naghizade, S., Mohammadi, S., Khoshshima, H.: Design and simulation of an all optical 8 to 3 binary encoder based on optimized photonic crystal or gates. J. Opt. Commun. 410, 793–798 (2018). https://doi.org/10.1515/joc-2018-0034

Neisy, M., Soroosh, M., Ansari-Asl, K.: All optical half adder based on photonic crystal resonant cavities. Photonic Netw. Commun. 35, 245–250 (2018)

Pahari, N., Guichhait, A.: All-optical Serial Data Transfer between Registers using optical non-linear materials. Optik (Stuttg) 123, 462–466 (2012). https://doi.org/10.1016/j.ijleo.2011.05.006

Parandin, F., Malmir, M.R., Naseri, M., Zahedi, A.: Reconfigurable all-optical NOT, XOR, and NOR logic gates based on two dimensional photonic crystals. Superlattices Microstruct. 113, 737–744 (2018). https://doi.org/10.1016/j.spmi.2017.12.005

Poustie, A., Manning, R.J., Kelly, A.E., Blow, K.J.: All-optical binary counter. Opt. Express. 6, 69 (2000). https://doi.org/10.1364/oe.6.000069

Qiu, M.: Effective index method for heterostructure-slab-waveguide-based two-dimensional photonic crystals. Appl. Phys. Lett. 81, 1163–1165 (2002). https://doi.org/10.1063/1.1500774

Raei, R., Ebnaei-Heidari, M., Saghafi, H.: Supercontinuum generation in organic liquid-liquid core-cladding photonic crystal fiber in visible and near-infrared regions. J. Opt. Soc. Am. B. 35, 323-330 (2018). https://doi.org/10.1364/josab.35.001545

Rahmani, A., Mehdizadeh, F.: Application of nonlinear PhCRRs in realizing all optical half-adder. Opt. Quantum Electron. 50, 30 (2018). https://doi.org/10.1007/s11082-017-1301-3

Rakhshan, M.R., Mansouri-Birjandi, M.A.: Realization of tunable optical filter by photonic crystal ring resonators. Optik (Stuttg) 124, 5377–5380 (2013). https://doi.org/10.1016/j.ijleo.2013.03.114
Rao, D.G.S., Palacharla, V., Swarnakar, S., Kumar, S.: Design of all-optical D flip-flop using photonic crystal waveguides for optical computing and networking. Appl. Opt. 59, 7139–7143 (2020)

Saghaei, H.: Supercontinuum source for dense wavelength division multiplexing in square photonic crystal fiber via fluidic infiltration approach. Radioengineering. 26, 16–22 (2017). https://doi.org/10.13164/re.2017.0016

Saghaei, H.: Dispersion-engineered microstructured optical fiber for mid-infrared supercontinuum generation. Appl. Opt. 57, 5591-5598 (2018). https://doi.org/10.1364/ao.57.005591

Saghaei, H., Ghanbari, A.: White light generation using photonic crystal fiber with sub-micron circular lattice. J. Electr. Eng. 68, 282–289 (2017). https://doi.org/10.1515/jee-2017-0040

Saghaei, H., Van, V.: Broadband mid-infrared supercontinuum generation in dispersion-engineered silicon-on-insulator waveguide. J. Opt. Soc. Am. B. 36, A193-A202 (2019). https://doi.org/10.1166/josab.36.00a193

Saghaei, H., Ebnali-Heidari, M., Moravvej-Farshi, M.K.: Mid-infrared supercontinuum generation via As2Se3 chalcogenide photonic crystal fibers. Appl. Opt. 54, 2072-2079 (2015). https://doi.org/10.1364/ao.54.002072

Saghaei, H., Heidari, V., Ebnali-Heidari, M., Yazdani, M.R.: A systematic study of linear and nonlinear properties of photonic crystal fibers. Optik (Stuttgart) 127, 11938–11947 (2016). https://doi.org/10.1016/j.ijleo.2016.09.111

Saghaei, H., Moravvej-Farshi, M.K., Ebnali-Heidari, M., Moghadasi, M.N.: Ultra-wide mid-infrared supercontinuum generation in As40Se60 chalcogenide fibers: solid core PCF versus SIF. IEEE J. Sel. Top. Quantum Electron. 22, 279-286 (2016). https://doi.org/10.1109/JSTQE.2015.2477048

Saghaei, H., Zahedi, A., Karimzadeh, R., Parandin, F.: Line defects on As2Se3-Chalcogenide photonic crystals for the design of all-optical power splitters and digital logic gates. Superlattices Microstruct. 110, 133–138 (2017). https://doi.org/10.1016/j.spmi.2017.08.052

Saghaei, H., Elyasi, P., Karimzadeh, R.: Design, fabrication, and characterization of Mach-Zehnder interferometers. Photonics Nanostruct. Fundam. Appl. 37, 100733 (2019). https://doi.org/10.1016/j.photonics.2019.100733

Sani, M.H., Tabrizi, A.A., Saghaei, H., Karimzadeh, R.: An ultrafast all-optical half adder using nonlinear ring resonators in photonic crystal microstructure. Opt. Quantum Electron. 52, 107 (2020). https://doi.org/10.1007/s11082-020-2233-x

Sharifi, H., Hamidi, S.M., Navi, K.: A new design procedure for all-optical photonic crystal logic gates and functions based on threshold logic. Opt. Commun. 370, 231–238 (2016)

Swarnakar, S., Kumar, S., Sharma, S.: Performance analysis of all-optical full-adder based on two-dimensional photonic crystals. J. Comput. Electron. 17, 1124–1134 (2018)

Tabrizi, A.A., Saghaei, H., Mehranpour, M.A., Jahangiri, M.: Enhancement of absorption and effectiveness of a perovskite thin-film solar cell embedded with Gold nanospheres. Plasmonics (2021). https://doi.org/10.1007/s11468-020-01341-1

Tavakoli, F., Zarrabi, F.B., Saghaei, H.: Modeling and analysis of high-sensitivity refractive index sensors based on plasmonic absorbers with Fano response in the near-infrared spectral region. Appl. Opt. 58, 5404-5414 (2019). https://doi.org/10.1364/AO.58.005404

Tavousi, A., Mansouri-Birjandi, M.A.: Optical-analog-to-digital conversion based on successive-like approximations in octagonal-shape photonic ring resonators. Superlattices Microstruct. 114, 23–31 (2018). https://doi.org/10.1016/j.spmi.2017.11.021

Tavousi, A., Mansouri-Birjandi, M.A., Ghadrdan, M., Ranjar-Torkamani, M.: Application of photonic crystal ring resonator nonlinear response for full-optical tunable add–drop filtering. Photonic Netw. Commun. 34, 131–139 (2017)

Uda, T., Ishii, A., Kato, Y.K.: Single carbon nanotubes as ultrasmall all-optical memories. ACS Photonics 5, 559–565 (2018). https://doi.org/10.1021/acsphotonics.7b01104

Vali-Nasab, A.M., Mir, A., Talebzadeh, R.: Design and simulation of all optical full-adder based on photonic crystals. Opt. Quantum Electron. 51, 56 (2019). https://doi.org/10.1007/s11082-019-1881-1

Younis, R.M., Areek, N.F.F., Obayya, S.S.A.: Fully integrated and and or optical logic gates. IEEE Photonics Technol. Lett. 26, 1900–1903 (2014). https://doi.org/10.1109/LPT.2014.2340435

Zamanian-Dehkordi, S.S., Soroosh, M., Akbarizadeh, G.: An ultra-fast all-optical RS flip-flop based on nonlinear photonic crystal structures. Opt. Rev. 25, 523–531 (2018)

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