S. Naghizade* and H. Khoshsima

Low Input Power an All Optical 4 × 2 Encoder based on Triangular Lattice Shape Photonic Crystal

https://doi.org/10.1515/joc-2018-0019
Received February 3, 2018; accepted February 27, 2018

Abstract: An all optical encoder based triangular lattice shape photonic crystal (PC) is proposed. The device is composed of two ring resonator waveguides and two OR gate with four input ports waveguides and two output ports waveguides in triangular lattice shape PC. The band diagram of base PC structure calculated by plane wave expansion (PWE) method. Also, transmission and distribution of electrical field behaviors of the proposed device are verified by two dimensional finite difference time domain (2D-FDTD) method. The proposed 4×2 encoder can operate at third communication window range, considering definitions of logic 0 and 1 being the normalized transmission as less than 3% and greater than 95% respectively. Despite the nonlinear encoders, in our case, due to the non-use of non-linear effects such as Kerr effect, low input power required for encoder.

Keywords: optical encoder, photonic crystal, ring resonator, OR gate

1 Introduction

Recently optical computing devices based on photonic crystals (PCs) structures that are applied in optical computing and signal processing [1, 2] has received more attention. Various sort of high speed optical communication systems have been implemented in various all-optical logic gates and encoder applications based on PCs [3–6]. However, most PC based logic gates are still limited by their complex arrangements of crystal rods, which can cause the component to generate extremely undesirable factors. In addition, significantly small number of all optical logic components can be operated on more of computing wavelengths; for logic gate applications and optical processing systems. Beside the optical logic gates, encoders [7, 8, 7–10, 11], optical filters [12–17], demultiplexers [18–24], switches [25–29], decoders [30, 31] as well as optical memories and optical modulators [32–35] are other cases of key optical components designed based on PCs. Optical encoders are the devices with 2^N input and N output ports (OUTs). This means that optical encoder is a logic device that designed for generating N-bit binary codes out of 2^N input ports (INs). Theses ports are binary ports, so they can suppose 0 or 1 values. At any given time only one of 2^N INs can be active (logic 1), and the other ports should be inactive (logic 0). Considering that which IN is active, an N-bit binary code will be harvested at the OUTs. Also optical encoder is a fundamental level in optical analogue to digital converters (ADCs) for introducing a suitable binary digital code from the opposite levels of input analog signal [36–38]. So far several designs have been proposed for realizing PC based optical encoders. Moniem [36] combined four resonant rings with T-waveguide to design a four – two optical encoder. The switching speed and foot print of this encoder is 500 GHz and 1225 μm^2. Alipour-Banaei et al. [37] proposed PC based encoder by used self-collimation property. The main drawback of their work is high sensitivity upon the phase of input signals. Hassangholizadeh-Kashtiban et al. [38] proposed an optical reversible encoder by combining nonlinear Kerr effect with elliptical resonant rings.

In this paper we used the triangular array structures to embed dielectric rods in the air background to create a two dimensional PC all optical encoder without using nonlinear Kerr effect that makes low input power property. Optical encoders based on nonlinear-Kerr effect, needs to high input power for appearing nonlinearity and this issue causes some unwanted effects such as: increasing the temperature of device and enhancing the probability of damaging which is undesirable. The main layout involved three hexagonal ring resonator filters, four linear waveguides as INs, and two OR gates. Our proposed encoder was able to operate in third communication window range. For analyzing and simulating the proposed structure and

***Corresponding author: S. Naghizade,** Young Researchers and Elite Club, Tabriz Branch, Islamic Azad University, Tabriz, Iran, E-mail: msmsenr@gmail.com
H. Khoshsima, Photonics Department, Research Institute for Applied Physics and Astronomy (RIAPA), University of Tabriz, 51665-163 Tabriz, Iran

Published online March 9, 2018

obtaining its optical behavior, we used RSoft Photonic CAD software, which perform the simulations based on plane wave expansion (PWE) [39] and finite difference time domain (FDTD) methods [40].

2 Design procedure

The logic circuit of a typical proposed 4×2 encoder is composed of four INs, three ring resonator filter, two OR gates in a two dimensional photonic crystal, as shown in Figure 1(b) which is formed of a triangular lattice of infinite circular dielectric rods emerged in air background. A, B, C and D are INs and O1 and O2 are the OUTs. So for realizing the proposed optical four – two encoder first we have to design a ring resonator filter and logic OR gate. The waveguides are formed by removing some of the dielectric rods from the two dimensional photonic crystal in xz plane. The refractive index and radius of dielectric rods are 3.43 and $r = 0.23 \times a$, respectively where $a = 538$ nm is the lattice constant of the PC. In the first step of our designing procedure we must calculate the band structure of bulk PC structure. In order to calculate photonic band gap (PBG) numerical methods are the best candidate. PWE is one of the numerical methods, which is used for extracting PBG by calculating Maxwell equation in frequency domain. The band structure of the fundamental PC is shown in Figure 2. According to Figure 2, the fundamental PC has two PBGs in TM mode and one PBG in TE mode. The first and widest PBG is in TM mode at $0.25 > a/\lambda < 0.37$, λ represents

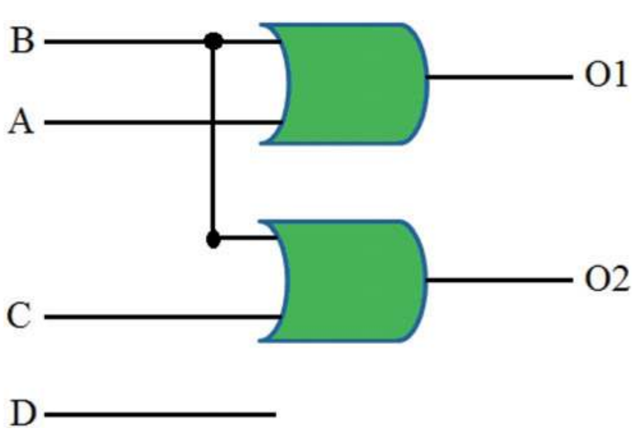

Figure 1: Schematic diagram of 4×2 encoder.

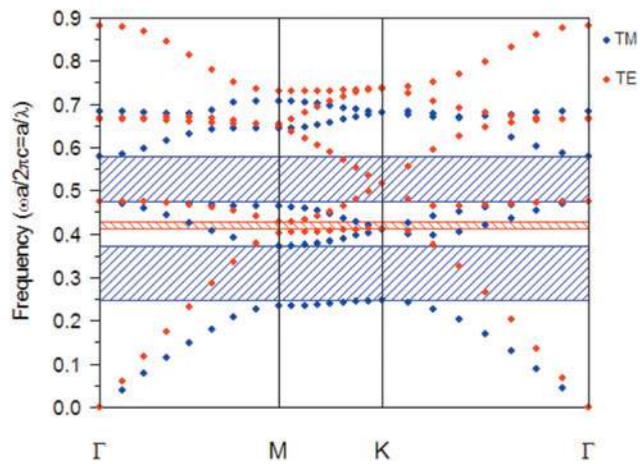

Figure 2: Band diagram of the base PC.

wavelength of electromagnetic wave. By choosing the lattice constant to be $a = 538$ nm, the PBG will be at $1454 \text{ nm} < \lambda < 2152$ nm, which completely covers the third communication window range, so the proposed structure will operate in this wavelength range.

2.1 Ring resonator filter

For design optical ring resonator filter which is one of the important parts of proposed encoder we used a 21×21 array of dielectric rods with aforementioned parameters as the fundamental PC. By removing the row of rods a line defect was created which can be used as an optical waveguide. To connect the IN to the OUT we put the one ring resonator that created by deleting some rods in the area of hexagonal shape ring in *xz* plane. The final sketch of proposed filter is shown in Figure 3(a). The transmittance spectra of the filer as shown in Figure 3(b). The results of Figure 3(b) shows the complete of wavelength $\lambda = 1550$nm coupled from port (IN) to port (OUT).

2.2 OR gate

For designing the OR gate required for realizing the proposed encoder, we used a 21×21 array of dielectric rods with aforementioned parameters as the fundamental PC. By removing appropriate dielectric rods two Y shaped waveguide have been created at the bends of

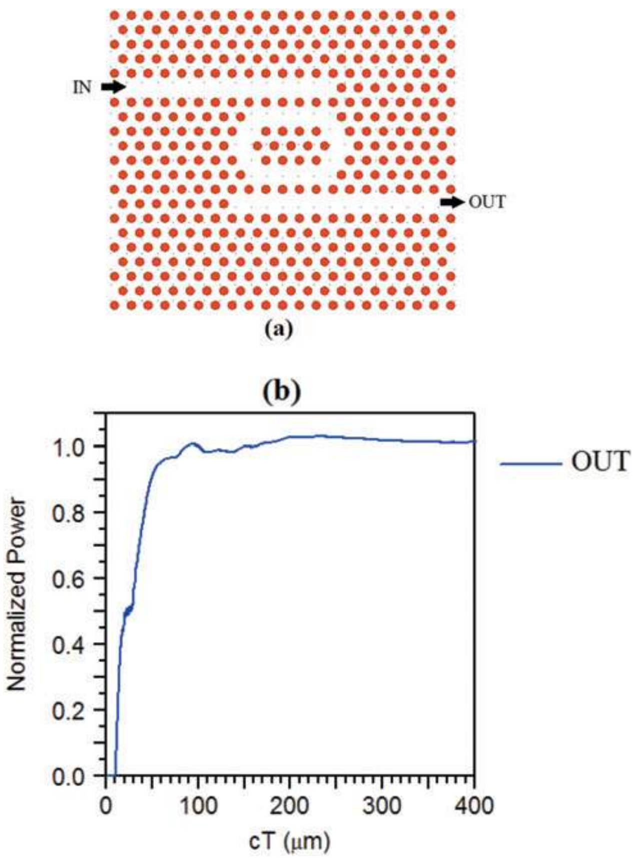

Figure 3: Final sketch of proposed ring resonator filter(a) and transmission spectra of filter(b).

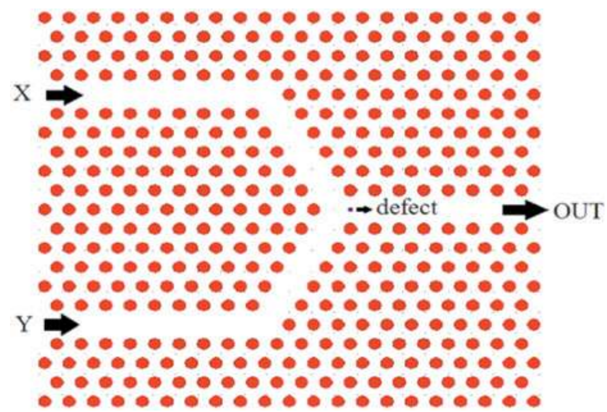

Figure 4: Final sketch of proposed OR gate.

the Y shaped waveguides. The cross section in which these waveguides were connected to each other we located a small defect rod ($r = 0.35 \times a$) at the beginning of output waveguide to increase the amount of optical waves traveling toward output waveguide. The proposed OR gate is shown in Figure 4. X and Y are the input ports and OUT is the output port of the proposed structure. For two input of OR gate, there are four possible combination of input states. The output port (OUT) will be OFF (logic 0) when both input ports are OFF (logic 0). However when any of the input ports or both of them are ON (logic 1) the output port will be ON (logic 1). These working states are shown in Figure 5(a)–(c) and summarized in Table 1. Also, the power level of the output port for different cases is shown in Figure 6(a)–(c). As shown in Figure 6, when one of the input ports is ON the amount of optical power for output port at the steady state is about 0.98 normalized powers and when both input ports are ON, it will be about 1.96 normalized power.

The proposed optical 4×2 encoder is shown in Figure 7 consists of PC based waveguides, ring resonators and OR gates that created in appropriate locations inside the fundamental PC structure. A, B, C and D are input ports and O1 and O2 are the output ports. In fact the proposed encoder made by combining the three folds designed ring resonator filters and two fold OR gates together.

3 Simulation and results

After finalizing the design procedure, we are going to simulate the proposed encoder and study its optical behavior. For this gain, we employed optical waves with $\lambda = 1550$ nm at each input ports. The all cases of the encoder are as follows:

Case1: when all input ports are OFF ($A = B = C = D = 0$) as shown in Figure 8(a) all of the output ports will be OFF, and the encoder generates “00” at the output ports. The amount of optical power at the output ports for this state is shown in Figure 9(a).

Case2: when $A = 1$ and $B = C = D = 0$, as shown in Figure 8(b) the light waves entering the device from input A will propagate inside waveguide and reach to the one of the input ports of first OR gate by ring resonator so this gate will be ON. When input A is ON, the encoder produces “10” binary code at the binary output ports. The amount of optical power at the output ports for this state is shown in Figure 9(b). One can see that the

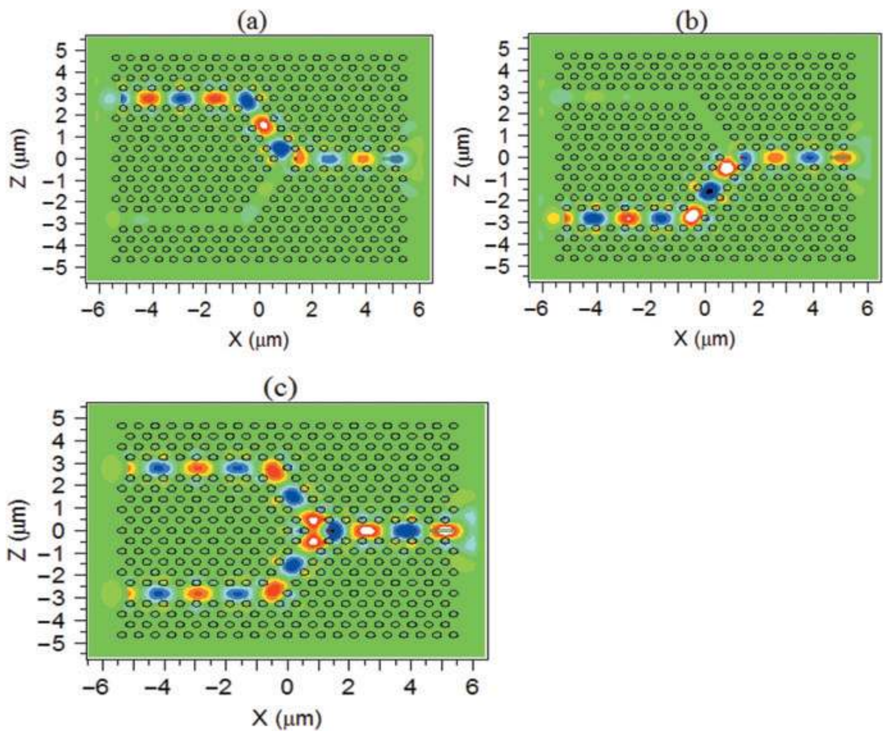

Figure 5: Different cases of the designed OR gate: (a) A = 1, B = 0, (b) A = 0, B = 1, and (c) A = B = 1.

Table 1: Input–output logical relationship table of OR gate.

Input X	Input Y	Out
0	0	0
1	0	1
0	1	1
1	1	1

optical normalized power, for port O1 and O2 is about 95 % and 0 % respectively.

Case3: when B = 1 and A = C = D = 0, one of the input ports of the both OR gates is ON, so according to Table 2, the output ports of the both OR gates (O1 and O2) will be ON. Also as shown in Figure 8(c) the light waves entering the device from port B by two ring resonators to one of the input ports of OR gates so the output ports O1 and O2 will be ON. Therefore when B is ON the encoder produces “11” binary code at the binary output ports. As shown in Figure 9(c) the amount of optical normalized power at both output ports O1 and O2 are 45.5 %.

Case4: when A = B = D = 0 and C = 1, as shown in Figure 8(d) the light waves entering the device from port C will propagate inside waveguide and reach to the one of the input ports of second OR gate by ring resonator so this gate will be ON. Thus, when input C is ON the encoder produces “01” binary code at the binary output ports. The amount of optical power at the output ports for this state is shown in Figure 9(d). One can see that the optical normalized power, for port O1 and O2 is about 0 % and 95 % respectively.

Case5: When A = B = C = 0 and D = 1 as shown in Figure 8(e) the input ports of the both OR gates are OFF, so all of the output ports will be OFF, and the encoder generates “00” binary code at the binary output ports. As shown in Figure 9(e) the amount of optical normalized power at both output ports O1 and O2 are 0 %.

These all cases of simulated encoder are summarized in Table 2. As shown in the optical power detecting from output ports for case 1 (A = 1 and B = C = D = 0),case 2 (A = C = D = 0 and B = 1) and case3 (A = B = D = 0 and C = 1) roughly have the same logic

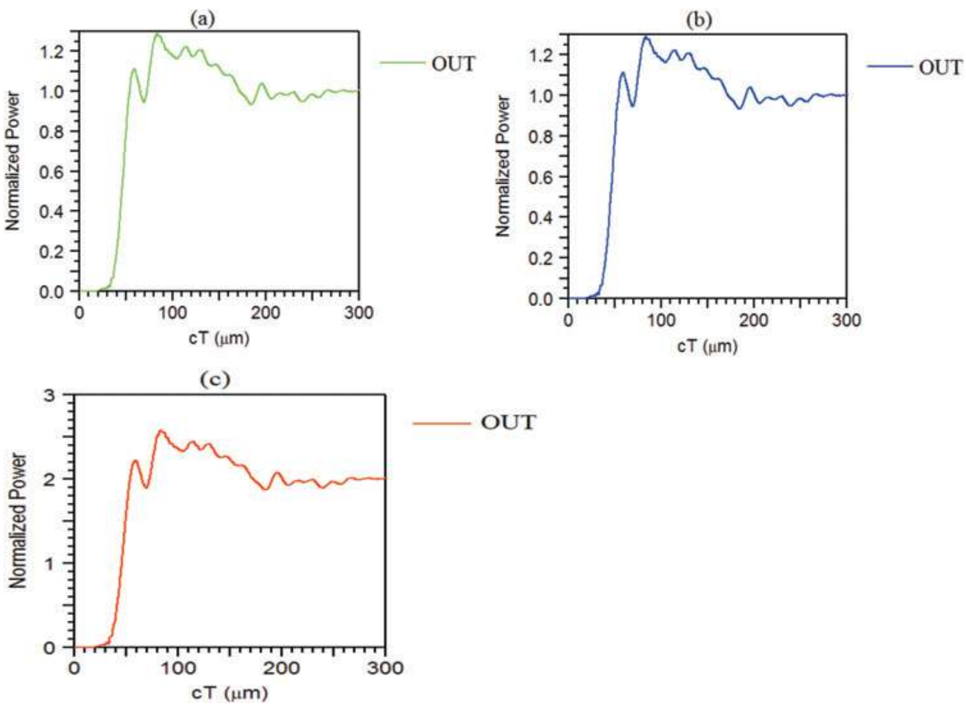

Figure 6: The normalized optical power at the output port when, (a) X port is ON, (b) Y port is ON and (c) X and Y ports are ON.

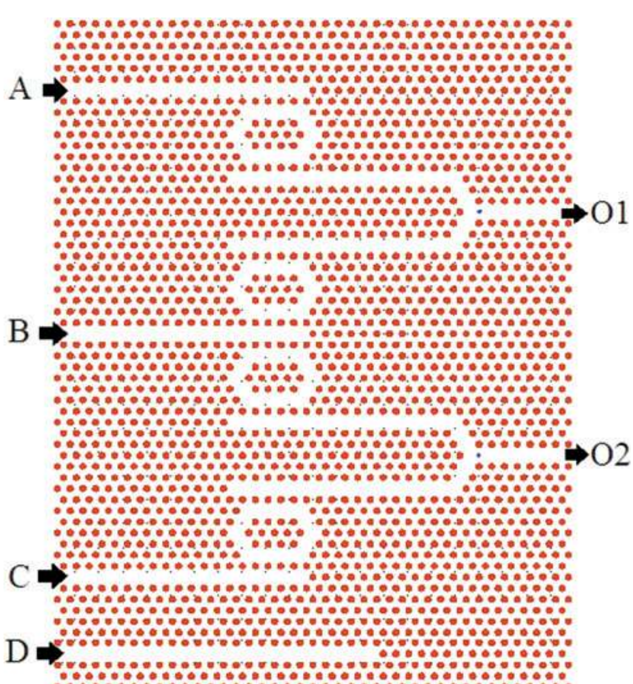

Figure 7: Final sketch of the proposed optical 4 × 2 encoder.

levels, but for the case1 (A = B = C = D = 0) and case4 (A = B = C = 0 and D = 1) it is different from other cases and the output power from ports O1 and O2 is zero. The total footprint of the proposed structure is about 723 μm^2 and it is good candidate for optoelectronic and optical circuits.

4 Conclusions

In summary, we proposed and investigated all optical 4 × 2 encoder based on PC structures. In the proposed structure without nonlinear optics we performed the switching tasks with low input power and very high speed performance. Each input port had a corresponding output port. Logic 0 and logic1 were defined under the 3 % and over the 95 % transmission, respectively. They exhibited a high contrast ratio, high transmission, and high compatibility. The proposed 4 × 2 encoder can be used as key component in third communication window range (1550 nm) and optical computing.

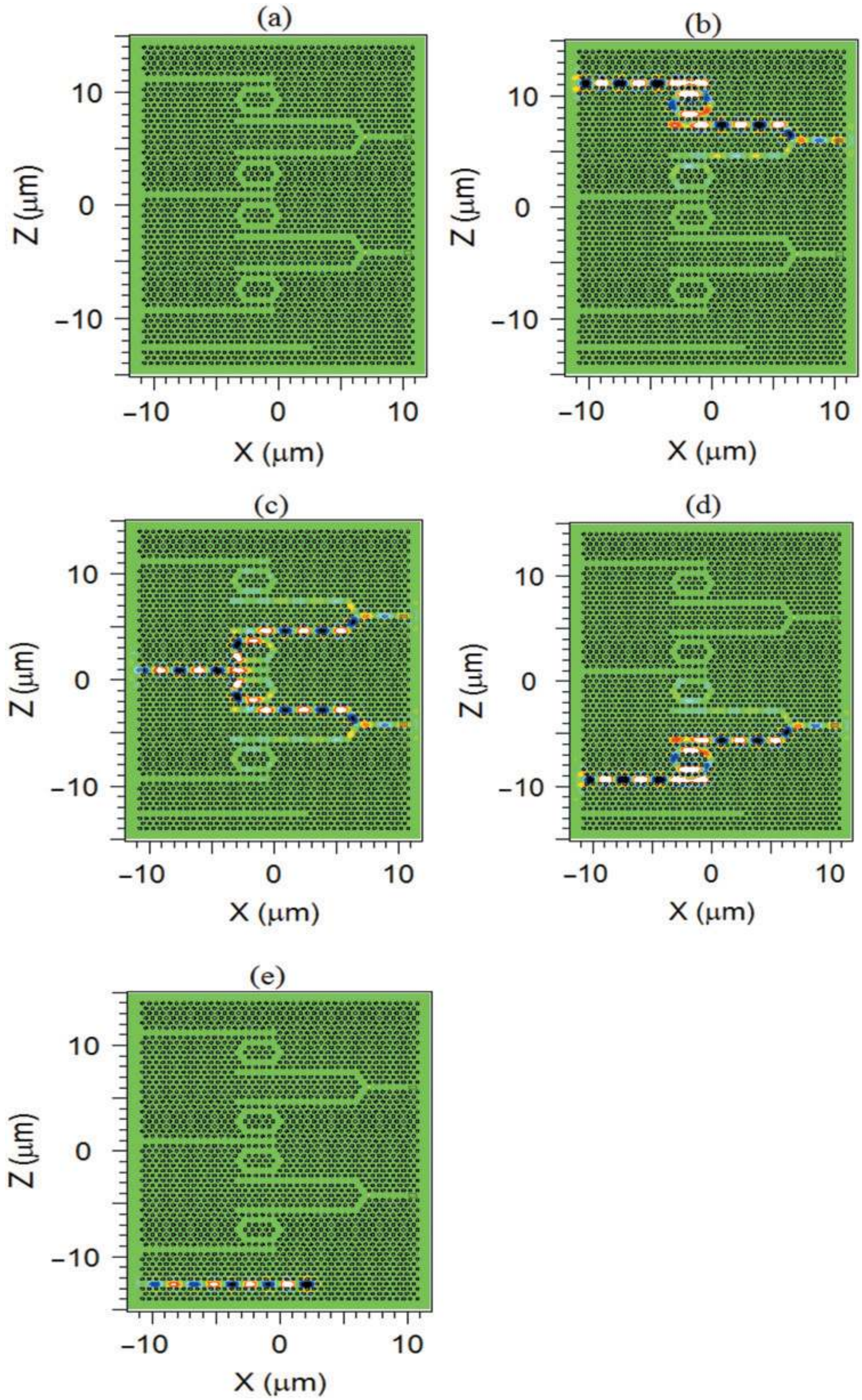

Figure 8: The cases of the proposed encoder, (a) A = B = C = D = 0, (b) A = 1 and B = C = D = 0 (c) B = 1 and A = C = D = 0, (d) A = B = D = 0 and C = 1,(e) A = B = C = 0 and D = 1.

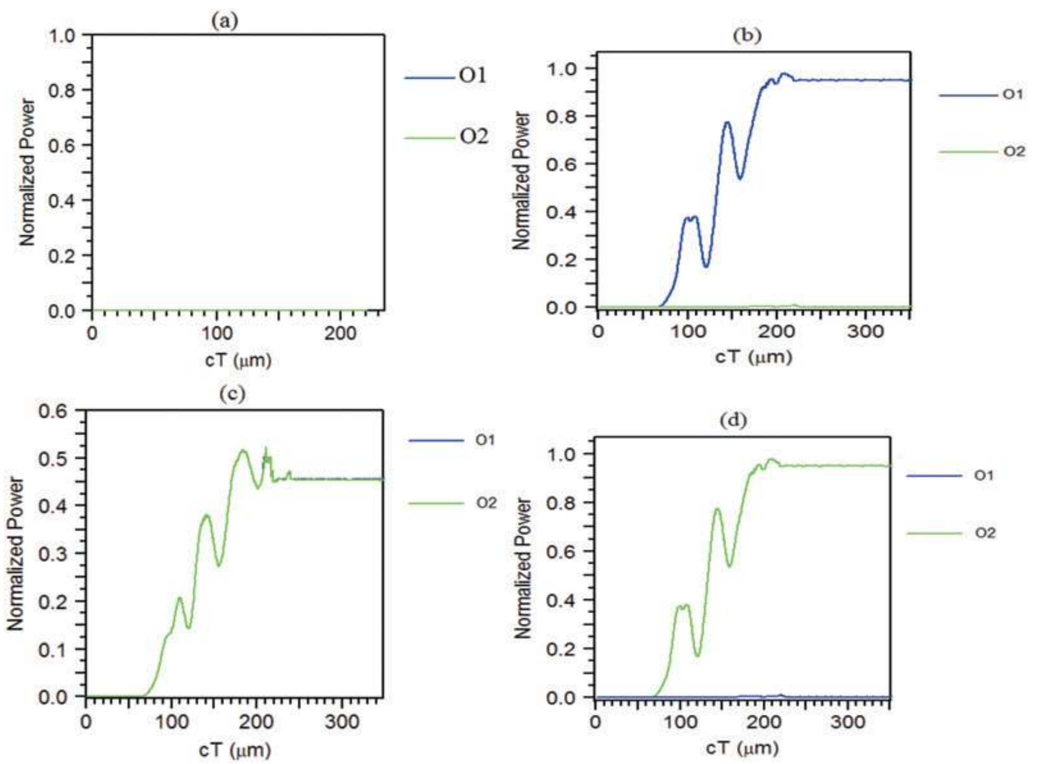

Figure 9: The output power of the proposed encoder when, (a) A = B = C = D = 0, (b) A = 1 and B = C = D = 0 (c) B = 1 and A = C = D = 0, (d) A = B = D = 0 and C = 1, (e) A = B = C = 0 and D = 1.

Table 2: All cases of the proposed 4 × 2 encoder.

Inputs				Power states		Logic levels	
A	B	C	D	O1	O2	O1	O2
0	0	0	0	0	0	0	0
1	0	0	0	0.95 I_{in}	0.03I_{in}	1	0
0	1	0	0	0.455I_{in}	0.455I_{in}	1	1
0	0	1	0	0.03I_{in}	0.95 I_{in}	0	1
0	0	0	1	0	0	0	0

References

1. John S. Strong localization of photons in certain disordered dielectric superlattices. Phys Rev Lett. 1987;58(23):2486–89.
2. Yablonovitch E. Inhibited spontaneous emission in solid-state physics and electronics. Phys Rev Lett. 1987;58(20):2059–62.
3. Ibrahim TA, Grover R, Kuo LC, Kanakaraju S, Calhoun LC, Ho PT. All-optical AND/NAND logic gates using semiconductor micro-resonators. IEEE Photonic Technol Lett. 2003;15:1422–24.
4. Rozman J, Pletersek A. Linear optical encoder system with sinusoidal signal distortion below −60 dB. IEEE Trans Instrum Meas. 2010;59:1544–49.
5. Zhang Y, Lei L, Dong J, Zhang X. 40 Gbit/s four-input photonic digital priority encoder employing three parallel semiconductor optical amplifiers. Electron Lett. 2011;47:872–73.
6. Ma X, Huang J, Metra C, Lombardi F. Reversible gates and testability of one dimensional arrays of molecular QCA. J Elect Test. 2008;24:1244–45.
7. Rani P, Kalra Y, Sinha RK. Design of all optical logic gates in photonic crystal waveguides. Opt Int J Light Electron Opt. 2015;126(9–10):950–55.
8. Gupta MM, Medhekar S. All-optical NOT and AND gates using counter propagating beams in nonlinear Mach–zehnder interferometer made of photonic crystal waveguides. Opt Int J Light Electron Opt. 2016;127:1221–8.
9. Alipour-Banaei H, Serajmohammadi S, Mehdizadeh F. All optical NOR and NAND gate based on nonlinear photonic crystal ring resonators. Opt Int J Light Electron Opt. 2014; 125(19):5701–04.
10. Chattopadhyay T. All-optical modified Fredkin gate. IEEE J Sel Top Quantum Electron. 2012;18:585–92.
11. Bao J, Xiao J, Fan L, Li X, Hai Y, Zhang T, et al. All-optical NOR and NAND gates based on photonic crystal ring resonator. Opt Commun. 2014;329:109–12.
12. Naghizade S, Sattari-Esfahlan SM. Excellent quality factor ultra-compact optical communication filter on ring-shaped cavity. J Opt Commun. 2017. DOI:10.1515/joc-2017-0035
13. Robinson S, Nakkeeran R. Two dimensional photonic crystal ring resonator based add drop filter for CWDM systems. Optik. 2013;124:3430–35.
14. Rezaee S, Zavvari M, Alipour-Banaei H. A novel optical filter based on H-shaped photonic crystal ring resonators. Optik. 2015;126:2535–38.

15. Naghizade S, Sattari-Esfahlan SM. Loss-less elliptical channel drop filter for WDM applications. J Opt Commun. 2017. DOI:10.1515/joc-2017-0088
16. Wang Y, Chen D, Zhang G, Wang J, Tao S. A super narrow band filter based on silicon 2D photonic crystal resonator and reflectors. Opt Commun. 2016;363:13–20.
17. Zamani M. Photonic crystal-based optical filters for operating in second and third optical fiber windows. Superlattice Microstruct. 2016;92:157–65.
18. Venkatachalam K, Sriram Kumar D, Robinson S. Investigation on 2D photonic crystal-based eight-channel wavelength-division demultiplexer. Photon Netw Commun. 2016. DOI:10.1007/s11107-016-0675-7
19. Alipour-Banaei H, Mehdizadeh F, Serajmohammadi S. A novel 4-channel demultiplexer based on photonic crystal ring resonators. Optik. 2013;124:5964–67.
20. Rakhshani MR, Mansouri-Birjandi MA. Design and simulation of four-channel wavelength demultiplexer based on photonic crystal circular ring resonators for optical communications. J Opt Commun. 2014;35:9–15.
21. Naghizade S, Sattari-Esfahlan SM. High-performance ultra-compact communication triplexer on silicon-on-insulator photonic crystal structure. Photon Netw Commun. 2017. DOI:10.1007/s11107-017-0702-3
22. Naghizade S, Sattari-Esfahlan SM. Tunable high performance 16-channel demultiplexer on 2D photonic crystal ring resonator operating at telecom wavelength. J Opt Commun. 2018. DOI:https://doi.org/10.1515/joc-2017-0199
23. Naghizade S, Sattari-Esfahlan SM. An optical five channel demultiplexer-based simple photonic crystal ring resonator for WDM applications. J Opt Commun. 2018. DOI:10.1515/joc-2017-0129
24. Zhuang Y, Ji K, Zhou W. Design of a DWDM multi/demultiplexer based on 2-D photonic crystals. IEEE Photonics Technol Lett. 2016;28:1669–72.
25. Teo HG, Liu AQ, Singh J, Yu MB, Bourouina T. Design and simulation of MEMS optical switch using photonic bandgap crystal. Microsyst Technol. 2004;10(5):400–06.
26. Notomi M, Shinya A, Mitsugi S, Kira G, Kuramochi E, Tanabe T. Optical bistable switching action of Si high-Q photonic-crystal nanocavities. Opt.Express. 2005;13(7):2678.
27. Tanabe T, Notomi M, Shinya A, Mitsugi S, Kuramochi E. Fast on-chip all optical switches and memories using silicon photonic crystal with extremely low operating energy. In: Quantum Electronics and Laser Science Conference (QELS'05), QPDA5, Baltimore, May 22–27, 2005.
28. Alipour-Banaei H, Mehdizadeh F, Serajmohammadi S, Hassangholizadeh-Kashtiban M. A 2*4 all optical decoder switch based on photonic crystal ring resonators. J Mod Opt. 2014;62(6):430–34.
29. Zhang Y, Zhang Y, Li B. Optical switches and logic gates based on self-collimated beams in two-dimensional photonic crystals. Opt Express. 2007;15:9287–92.
30. Serajmohammadi S, Alipour-Banaei H, Mehdizadeh F. All optical decoder switch based on photonic crystal ring resonators. Opt Quantum Electron. 2014;47(5):1109–15.
31. Moniem TA. All optical active high decoder using integrated 2D square lattice photonic crystals. J Mod Opt. 2015; 62(19):1643–49.
32. Fekete L, Kadlec F, Kuzel P, Nemec H. Ultrafast opto terahertz photonic crystal modulator. Opt Lett. 2007;32:680–82.
33. Beggs D, White T, Cairns L, O'Faolain L, Krauss T. Demonstration of an integrated optical switch in a silicon photonic crystal directional coupler. Physica E. 2009;41:1111–14.
34. Gu L, Jiang W, Chen X, Wang L, Chen RT. High speed silicon photonic crystal waveguide modulator for low voltage operation. Appl Phys Lett. 2007;90:071105–071105-3.
35. Zhang X, Chung CH, Hosseini A, Subbaraman H, Luo J, Jen AK, et al. High performance optical modulator based on electro-optic polymer filled silicon solt photonic crystal wavguide. J Lightwave Technol. 2016;34:2941–51.
36. Moniem TA. All-optical digital 4 × 2 encoder based on 2D photonic crystal ring resonators. J Mod Opt. 2015;63:735–41.
37. Alipour-Banaei H, Rabati MG, Abdollahzadeh-Badelbou P, Mehdizadeh F. Application of self-collimated beams to realization of all optical photonic crystal encoder. Phys E Low Dimens Syst Nanostruct. 2016;75:77–85.
38. Hassangholizadeh-Kashtiban M, Sabbaghi-Nadooshan R, Alipour-Banaei H. A novel all optical reversible 4 9 2 encoder based on photonic crystals. Opt Int J Light Electron Opt. 2015;126:2368–72.
39. Johnson SG, Joannopoulos JD. Block-iterative frequency domain methods for Maxwell's equations in a plane wave basis. Opt Express. 2001;8:173–90.
40. Gedney SD. Introduction to Finite-Difference Time-Domain (FDTD) method for electromagnetics. Lexington, KY: Morgan&Claypool; 2010.