Investigation On Ultra-Compact, High Contrast Ratio 2d-Photonic Crystal Based All Optical 4 x 2 Encoder

R. Arun Kumar (✉ arunec002@gmail.com)

Mount Zion College of Engineering and Technology

Kavitha V

Mount Zion College of Engineering and Technology

Rama Prabha K

Mount Zion College of Engineering and Technology

Latha K

Mount Zion College of Engineering and Technology

Robinson S

Mount Zion College of Engineering and Technology

Research Article

Keywords: All-optical encoder, Photonic crystal, Switching speed, Finite difference time domain analysis, Plane-wave expansion

Posted Date: September 14th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-815039/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Optical encoder is playing an essential starring role in optical communication and computing applications. This paper presents a new structure for 4 x 2 optical encoder based on Two Dimensional Photonic Crystals (2DPC). The proposed structure consists of silicon rods in background of air using hexagonal lattice. The proposed structure is composed of four input waveguides and two outputs. The band structure is examined by Plane Wave Expansion (PWE) method and the performance parameters of the 4x2 encoder, namely, normalized output power, footprint, contrast ratio, response time and bit rate are analyzed using Finite Difference Time Domain (FDTD) method. The proposed encoder is operated at 1550nm. The low response time, and small footprint have shown that the encoder is exceptionally suitable for high performance optical networks and photonic computational integrated devices.

Introduction

Optical communication is one of the advanced technologies which create a tremendous impact nowadays. The researcher gives more attention to design optical devices, especially using Photonic Crystals (PC). PCs are engineered a periodic dielectric or metallo-dielectric nanostructures which is having different dielectric constant materials. It has three types based on its direction of dielectric constant variation in axis, such as, one, two and three dimensional PCs [1]. Among all, 2DPC is most widely used as it supports better confinement of light, easy to control the propagation and easy calculation of band gap and etc. [2]. Mainly the optical devices are designed by 2DPC, such as, Encoders, Decoders [3], Adders [4], Multiplexers and Demultiplexer [5], Isolators [6], Filters [7], Power splitter [8], Directional coupler, Circulator, logic gates [9, 10], Sensors [11, 12], Analog to digital converters [13], Comparator and so on.

In recent days, the PC based optical logical devices are essential components and highly suitable for all the logical functions due to the attractive features. Typically, optical encoder is the better device for optical computing that repeatedly devised with better performance parameters. The encoders generated output N-bit binary codes with 2^N inputs and optical encoders primarily designed by different methods for changing the operational state [i.e. "OFF" and "ON"], such as, varying the design parameters or structural parameters, modifying the materials and refractive index of PC, varying the launching angle of input electromagnetic signal, different defect mechanisms, self-collimated effects [14], interference based defects [15], multimode interference effect [16], Mach Zehnder interferometer [17] and nonlinear Kerr effects [18]. The functional parameters, namely, bit rate, response time/delay time, switching speed, footprint, operating wavelength, and contrast ratio are estimated.

In the literature, the interference/multi-interference based encoder is operated with self-imaging principle where input profile is reproduced with multiple copies at regular intervals along the propagation direction. It requires a precise phase control for each logic, which is really hard to achieve though it offers low loss and wide optical bandwidth [19]. In self-collimation method, a phase shifter is required, as the output depends upon the phase of the input signals which in turn leads large foot print [20, 21]. The waveguide

and ring resonator based encoders are reported with T shape, L shape and Y shape waveguide and square, quasi-square, hexagonal, elliptical and circular shape ring resonators [22–27].

From the literature analysis, the encoders are reported with the above mentioned techniques using linear and nonlinear materials. The high input power required for non-linear materials. Though it has high contrast ratio it has some drawback such as the temperature of the device will increase and it is difficult to integrate the silicon optical devices. The linear materials offer less input power, high switching speed and also it provides better performance parameters. Hence, the proposed 4*2 encoder designed using linear materials which offers better contrast ratio, bit rate and delay time. The output spectrum and band gap are examined by Plane Wave Expansion (PWE) and Finite Difference Time Domain (FDTD), respectively. The rest of the paper is organized as follows: Section II describes the structural designs and simulation results of 4*2 encoder are presented in Section III, Section IV concluded the proposed work.

Structural Design Of Proposed Structure

The basic functionality of the encoder is to produce N-codes output concerning the 2^N input ports which is shown in Fig. 1. The truth table of 4 x 2 encoder is shown in Table 1, it has four binary code inputs (A_0, A_1, A_2, A_3) and two binary code outputs (B_0, B_1).

Table 1 Logic function of 4x2 encoder

INPUT				OUTPUT	
A_0	A_1	A_2	A_3	B_0	B_1
1	0	0	0	0	0
0	1	0	0	1	0
0	0	1	0	0	1
0	0	0	1	1	1

The proposed encoder is designed using 2DPC based triangular/hexagonal lattice. The proposed encoder structure consists of 29 x 21 circular cylindrical silicon (Si) rods immersed in air. The structural parameters, namely, refractive index of the material 3.46, rods radius of 100nm and the lattice constant of $a = 540\text{nm}$ are used.

Fig. 2 shows the band diagram of the periodic 2DPC structure. It has TM PBG and TE PBG. From that regions, an immense TE polarization is the suitable polarization for the light propagation, as far as the normalized frequency range from $0.325 a/\lambda$ to $0.44 a/\lambda$, whose the corresponding wavelength of the region limited from 1227nm to 1661nm. All the simulation is done in the range of the wavelength and the range highly appropriate for the third telecommunication window. The wavelength for this simulation is 1550nm.

The proposed 4*2 encoder is designed using four inputs A_0, A_1, A_2, A_3 as linear waveguide and two Y shaped output waveguides (B_0, B_1). The A_0 waveguide is formed by removing the crystal rods in the plane direction inside the structure and connected to binary code input A_0 . When the binary code input A_0 is high, both output need to zero, for the purpose the waveguide is created with a minimum short dimension and it is not connected to the output port. Similarly, the waveguide A_1, A_2, A_3 created by the parallel of A_0 and those waveguides performed as input ports A_1, A_2, A_3 . The Y-shaped waveguides have made in between the A_1, A_2 and A_3 input waveguide. The nano coupling rods N_1, N_2, N_3 , and N_4 are positioned between the input waveguides (A_1, A_2, A_3) and the output waveguide (B_0, B_1). The coupling rods are formed by reducing the radius of the silicon rods in 50nm, in order to split the input power equally in all different states. It is primarily used to increase the coupling between the input and output signal transmission, which is used to reduce the reflection losses and improve an encoder's output power.

Simulation Results And Discussion

The output power is calculated at the output port with respect to the input signal using the following equation.

$$T(f) = \frac{1/2 \int \text{real}(p(f)^{\text{monitor}}) dS}{\text{SourcePower}} \quad (1)$$

where, $T(f)$ represents the normalized transmission, $p(f)$ represents the pointing vector and dS represents the surface normal.

The Perfect Matched Layer (PML) is incorporated to minimize to reflection which is an artificial boundary layer to support the simulation in open boundary condition. It strongly absorbs all the incident waves in all directions, without any reflection inside the PC lattice.

$$\Delta t \leq \frac{1}{c \sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta z^2}}} \quad (2)$$

where Δt denotes the step time, C denotes the speed of light in free space, respectively.

The Gaussian optical signal is applied to the four input ports, namely A_0, A_1, A_2 , and A_3 . The 1mW of input power is applied at 1550nm for simulation. The proposed encoder structure is simulated using the 2D FDTD method and the performance parameters are examined. In the proposed structure, the nano coupling rods (N_1, N_2, N_3, N_4) are working as a digital switch between input and output waveguides which in turn enhancing the coupling between the input and output ports. In this simulation, the input power is considered P_i , the output power is P_o , and normalized power is treated as $P_n = P_o/P_i$. In this case, the normalized power level at the output port is resulted the logical level, such as, 'ON' or 'OFF' state. If P_o is underneath 0.25mW, it is treated as logic '0' and the P_o is directly above the level of 0.25mW that is assumed as logic '1'.

State 1: For a given logic input of 1000, $A_0=1$ i.e. is 'ON' and A_1, A_2, A_3 are 'OFF', the Gaussian input signal is not entered inside the waveguide. In this case, the input signal is entered into A_0 input port and signal is blocked due to the arrangement waveguide A_0 . Hence, there is no power is directed to the output port B_0 and B_1 (00) as shown in Fig. 4(a). The output power P_0 is 0.0062 at B_0 and 0.0001 at B_1 , hence, the normalized transmission power is 0%. The electromagnetic field distribution is displayed as inset in Fig. 4(a).

State 2: For the logic input of 0100, A_1 input is 'ON', and A_0, A_2, A_3 inputs are 'OFF' state. Then input signal is passed into the A_1 input port and the signal is coupled through the N_1 Nano coupling rods. Hence the output port B_0 is 'ON' and B_1 is 'OFF' state as shown in Fig. 4(b). The normalized power level at output port B_0 is around 99.8% and 0.0052% power level obtained in another output port B_1 and the field distribution is displayed as inset in Fig. 4(b).

State 3: The logic input 0010 is given, the input port $A_2=1$ is 'ON' state and the other inputs are retained in 'OFF' condition. The input power applied to port A_2 and then the input signal is coupled through the N_4 coupling rods in the B_1 output port and the encoder generates the output 01 as depicted in Fig. 4(c). The power level at B_0 is 0.0052% and 99.8% of power level is obtained in output port B_1 . The inset in Fig. 4(c) shows the field distribution when the input is 0010.

State 4: For logic input 0001, A_3 is 'ON' and A_0, A_1, A_2 inputs are in 'OFF' condition. Then input signal is applied to port A_3 and then the light propagates in both Y shaped waveguides and the input signal is coupled through the N_2 and N_3 coupling rods which generate high output power in both output ports B_0 and B_1 as depicted in Fig. 4(d) inset. In this case, the encoder generates the output 11 as shown in Fig. 4(d). As displayed in Fig. 4(d), the normalized power level at B_0 is $0.5311P_i$ and B_1 is $0.5311 P_i$ and the normalized transmission power is 53.11%.

The contrast ratio of the nano-optical encoder is defined by taking logarithmic function of the normalized output power of logic 1 to logic 0 as follows,

$$CR = 10 \log \left(\frac{P_1}{P_0} \right) dB \quad (3)$$

For different logic combination, the simulation of signal propagation is providing analytical graph with power versus time. And this process is used to find the functional parameters, such as, normalized output power, contrast ratio, response time and bit rate. The P_1 and P_0 indicate the normalized power of logic '1' and logic '0', respectively.

The response time and data rate are primarily calculated from the time-evolving curve as in Figs. 4(a) – 4(d). The response time is expressed as the time taken for the output signal to reach a quarter of the power range in the time response of the normalized curve. The data rate is calculated as the reciprocal of the response time. When the input is either 1000 or 0001, the output for 'ON' & 'OFF' state is remaining

same, hence, the contrast ratio is estimated for the input 0100 and 0010. For different logic level outputs are achieved from the input level of 0100 and 0010 and the output power level of 0.9980 and 0.0052 are examined and the contrast ratio is 22.83 dB, respectively. The logic output 01 and 10, the response time and data rate are 0.228ps and 4.38Tbps, respectively. Another logic output 11, the response time and data rate are 0.235ps and 4.25Tbps, respectively. From Table 2, the minimum contrast ratio, maximum delay time and the minimum data rate of the proposed optical encoder is 22.83 dB, 0.235ps and 4.25Tbps, respectively, which are listed in Table 2.

Table 2. Logic input, Output power, Response time Bit rate and Contrast ratio of proposed 4x2 encoder

Input Ports				Output Ports		Response Time (ps)	Data rate (Tbps)	Contrast Ratio (dB)
A ₀	A ₁	A ₂	A ₃	B ₀	B ₁			
1	0	0	0	0.0062	0.0001	**	**	**
0	1	0	0	0.9980	0.0052	0.228	4.38	22.83
0	0	1	0	0.0052	0.9980	0.228	4.38	22.83
0	0	0	1	0.5311	0.5311	0.235	4.25	**

Table 3. Functional parameters comparison of proposed encoders with reported encoders

References	Lattice	Defects	Contrast Ratio (dB)	Response Time (ps)	Bit Rate (Tbps)	Footprint in μm^2
[28]	Cubic/Square	Circular Ring resonator	05.86	3	3.3	612
[29]	Cubic/Square	Square Ring resonator	17.78	1	1	1927
[30]	Cubic/Square	Line and Point defect	07.30	0.2	4.1	880
[31]	Cubic/Square	Circular Ring resonator	07.11	**	**	128.5
[32]	Cubic/Square	Circular Ring resonator	12.80	***	***	1794
[33]	Hexagonal	Line and Point defect	03.71	1.40	0.71	3795
[34]	Hexagonal	Circular Ring resonator	11.80	0.70	1.42	625.0
[35]	Cubic/Square	Square Ring resonator	09.54	***	***	240.5
[36]	Hexagonal	Circular Ring resonator	05.70	1.00	1.00	218.6
[37]	Cubic/Square	Square Ring resonator	09.24	1.80	0.84	795.6
Proposed work	Hexagonal	Line and Point defect	22.83	0.235	4.34	178.1

The primary parameters of the encoder, such as, type of lattice, type of defects, contrast ratio, response time, bit rate and foot print of the proposed encoders is compared with the reported encoders which are listed in Table 3. The encoders are devised using cubic or hexagonal lattice. The ring resonator and point and line defect mechanism are predominantly incorporated. The contrast ratio, bit rate and size of the proposed encoder is 22.83dB, 4.34Tbps and 178.1 μm^2 which is better than the reported one. In Ref. 30, the response time is 0.2ps, however, the contrast ratio is lower and the size is larger. Typically, in the reported encoders, if the contrast ratio is increased, the response time is decreased. On the other hand, if the response time is improved, it confines the contrast ratio. In addition, if the contrast ratio, bit rate and response time are superior, the size of the encoder is larger. However, the proposed encoder provides significant improvement in all the parameters with the compact size than the reported encoders. Hence, the proposed encoders are used for high speed computing photonic integrated circuits.

Conclusion

In this attempt, the 2DPC based 4x2 encoder is devised by arrangement of silicon rods with background air substrate in a hexagonal lattice. In order to reduce the power loss and to avoid the obstacles during the signal propagation the line and point defects are introduced in this proposed design. It operates at a wavelength of 1550 nm. The normalized output efficiency obtained as 100%. The performance of the device is simulated using FDTD method. The proposed encoder performance parameters are examined such as: contrast ratio of 22.83 dB, response time of 0.235 ps, bit rate of 4.34 Tbps and the size of $178.1\mu\text{m}^2$. Hence, the proposed design is suitable for photonic integrated circuits and optical networks.

Declarations

I declare that the work carried out by the authors alone. Whole or any other part of this work has not been submitted before in any other journals.

Funding Statement

Not Applicable

Competing interests

The authors declare that there are no competing interests related to this article.

Authors' contributions

All Authors are responsible for the correctness of the statements provided in the manuscript. The following contributions have been made by the Authors. RA is calculated the structural parameters, such as, radius of the rod, lattice constant and refractive index, designed and simulated the proposed 4 x 2 encoder. The electric field distribution, output response, bit rate, contrast ratio, response time is analyzed by RA, VK, KR and KL. SR is given the idea, verify the all the simulated results and corrected the manuscript. Authors read and approved the final manuscript.

Availability of data and material

Yes. It is available.

Compliance with ethics standards

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Acknowledgment

Not applicable.

References

1. Joannopoulos, D.J., Steven Johnson, G., Winn, N.J., Meade, R.D.: Photonic Crystals: Modeling the Flow of Light, **second. ed.**, Princeton University Press (2008)
2. Guilian Yi, Byeng D. Youn, **"A comprehensive survey on topology optimization of phononic crystals"**, Journal of Structural and Multidisciplinary Optimization, **54(5)**,1315–1344 (2016).
3. Mehdizadeh, F., Soroosh, M., Alipour-Banaei, H., Alipour-Banaei, amed, Mahdizadeh, F., Serajmohammadi, S.: A novel proposal for optical decoder switch based on photonic crystal ring resonators. Opt. Quant. Electron. **48(20)**, 1–9 (2016)
4. Mona Neisy, M., Soroosh, K., Ansari-Asl: All optical half adder based on photonic crystal resonant cavities. Journal of Photon Network Communication **35(2)**, 245–250 (2018)
5. Balaji, V.R., Murugan, M., Robinson, S., Nakkeeran, R.: Design and optimization of photonic crystal based eight channel dense wavelength division multiplexing demultiplexer using conjugate radiant neural network. Journal of Optical and Quantum Electronics **49(198)**, 1–15 (2017)
6. Wang, Y., Biaogang, Xu, Zhang, D., Xu, S., Dong, Z., Zeng, X., Pei, X.J.: Magneto-Optical Isolator Based on Ultra-Wideband Photonic Crystals Waveguide for 5G Communication System. Crystals **9(570)**, 1–9 (2019)
7. Savarimuthu Robinson, R., Nakkeeran: Photonic crystal ring resonator-based add drop filters: a review. Opt. Eng. **52(6)**, 1–12 (2013)
8. Arunkumar, R., Jayson, K., Jayabarathan, S., Robinson: Design and analysis of optical Y-splitters based on two-dimensional photonic crystal ring resonator. J. Optoelectron. Adv. Mater. **21(7–8)**, 435–442 (2019)
9. K.RamaPrabha, S.Robinson, "Ultra Compact, High Contrast Ratio Based all Optical OR Gate Using Two Dimensional Photonic Crystals" <https://doi.org/10.1007/s12633-020-00811-9>,(2020)
10. Jayson, K., Jayabharathan, G..Subhalakshmi, S.Robinson: Performance evaluation of Two dimensional photonic crystal all optical AND/OR logic gates. Journal of Optical Communications **39(3)**, 1–11 (2018)
11. Arunkumar, R., Suganya, T.: S.Robinson, "Design and Analysis of 2D Photonic Crystal Based Biosensor to Detect Different Blood Components". Photonic Sensors **9(1)**, 69–77 (2019)
12. Bahabady, A.M., Olyaei, S., Arman, H.: Optical Biochemical Sensor Using Photonic Crystal Nano-ring Resonators for the Detection of Protein Concentration. Current Nanoscience **13(4)**, 421–425 (2017)
13. Bahar Youssefi, M.K.M., Farshi, N., Granpayeh: Two bit all-optical analog-to-digital converter based on nonlinear Kerr effect in 2D photonic crystals. Opt. Commun. **285**, 3228–3233 (2012)

14. Zhang, Y., Zhang, Y., Li, B.: Optical switches and logic gates based on self-collimated beams in two-dimensional photonic crystals. *Journal of Optics Express* **15**(15), 9287–9292 (2007)
15. Nirmala Maria, D., Vincent Mathew, “Interference based square lattice photonic crystal logic gates working with different wavelengths”, *Journal of Optics and Laser Technology*, 80, 214–219: (2016)
16. Chunrong Tang, Xinyu Dou, Yuxi Lin, Wu, Hongxi Yin, B., Zhao, Q.: Design of all-optical logic gates avoiding external phase shifters in a two-dimensional photonic crystal based on multi-mode interference for BPSK signals. *Journal of Optics Communication* **316**(1), 49–55 (2014)
17. Alejandro Martínez, P., Sanchis, Marti, J.: Mach–Zehnder interferometers in photonic crystals. *Journal of Optical and Quantum Electronics* **37**, 77–93 (2005)
18. Salmanpour, A., Mohammadnejad, S., Omran, P.T.: All-optical photonic crystal NOT and OR logic gates using nonlinear Kerr effect and ring resonators. *Journal of Optical and Quantum Electron* **47**(12), 3689–3703 (2015)
19. Salmanpour, A., Mohammadnejad, S., Bahrami, A.: Photonic crystal logic gates: an overview. *Journal of Optical and Quantum Electronics* **47**, 2249–2275 (2015)
20. Shaik, E.H., Rangaswamy, N.: Realization of XNOR logic function with all-optical high contrast XOR and NOT gates. *Journal of Opto-Electronics Review* **26**(1), 63–72 (2018)
21. Zhang, Y.L., Zhang, Y., Li, B.: Optical switches and logic gates based on self-collimated beams in two-dimensional photonic crystals. *Journal of optics Express* **15**(15), 9287–9292 (2007)
22. Hamed Seif-Dargahi, “Ultra-fast all-optical encoder using photonic crystal-based ring resonators”, *Photonic Network Communications*, 36(2), 272–277(2018)
23. Latha, K., Arunkumar, R., Rama Prabha, K., Robinson, S.: “Performance Analysis of all Optical 4*2 and 8*3 Encoder Using Two Dimensional Photonic Crystals Waveguides”, *Silicon*, <https://doi.org/10.1007/s12633-021-01107-2>, (2021)
24. Tamer, S., Mostafa, El- Sayed, M., El- Rabaie: Literature Review on All-Optical Photonic Crystal Encoders and Some Novel Trends. *Menoufia Journal of Electronic Engineering Research* **28**(2), 153–184 (2019)
25. Rafah, I.O.: A novel all optical 4x2 encoder switch based on photonic crystal ring resonators. *Optik Int Journal of Optics* **127**(19), 7835–7841 (2016)
26. Rajasekar, R., Thavasi, G., Raja, J.K., Jayabarathan, S., Robinson: High speed nano-optical encoder using photonic crystal ring resonator. *Photon Netw. Commun.* **40**, 31–39 (2020)
27. Neghizade, S., Khoshsima, H.: “Low input power an all optical 4x2 encoder based on triangular lattice shape photonic crystal”, *Journal Optics Communication.*, <https://doi.org/10.1515/joc-2018-0019>, (2018)
28. Fatemeh Hadadan, M., Soroosh: A New Proposal for 4-to-2 Optical Encoder using Nonlinear Photonic Crystal Ring Resonator. *Journal of Optics and Photonics* **13**(2), 119–126 (2019)
29. Siamak Gholamnejad, M., Zavvari: Design and analysis of all-optical 4 – 2 binary encoder based on photonic crystal. *Journal of Optical and Quantum Electronics* **302**(49), 1–12 (2017)

30. Mehdizadeh, F., Soroosh, M., Alipour-Banaei, H.: A proposed for 4-to-2 optical encoder based on photonic crystals. *IET Optoelectron.* **11**(1), 29–35 (2017)
31. Tamer, S., Mostafa, N.A., Mohammed, El-Sayed, M., El-Rabaie: Ultracompact ultrafast-switching-speed all-optical 4×2 encoder based on photonic crystal. *J. Comput. Electron.* **17**(1), 1–14 (2018)
32. Monisha, S., Saranya, D., Rajesh, A.: Design and analysis of multi hexagonal reversible encoder using photonic crystals. *Journal of Optical and Quantum Electronics* **51**(1), 1–12 (2018)
33. Alipour-Banaei, H., et al.: Application of self-collimated beams to realization of all-optical photonic crystal encoder. *Physica E* **75**, 77–85 (2016)
34. Naghizade, S., Khoshsim, H.: “Low Input Power an All-Optical 4 × 2 Encoder based on Triangular Lattice Shape Photonic Crystal”, *J. Opt. Commun*, <https://doi.org/10.1515/joc-2018-0019> (2018)
35. Ouahab, I., Naoum, R.: A novel all-optical 4× 2 encoder switch based on photonic crystal ring resonators. *Optik* **127**(19), 7835–7841 (2016)
36. Anagha, E.G., Rajesh, A., Saranya, D., “Design of an all-optical encoder using 2D photonic crystals”, 2nd International Conference on Inventive Systems and Control Proc, IEEE, 55–59: (2018)
37. Seif-Dargahi, H.: Ultra-fast all-optical encoder using photonic crystal-based ring resonators. *Photonic Network Communication* **36**, 272–277 (2018)

Figures

Figure 1

Block diagram of the encoder

Figure 2

The 4x2 encoder band diagram

Figure 3

The 4 x 2 encoder schematic layout

(a)

(b)

(c)

(d)

Figure 4

Output response of proposed 4x2 encoder design (a) $A_0=1, A_1=0, A_2=0, A_3=0$ and $B_0=0, B_1=0$, (b) $A_0=0, A_1=1, A_2=0, A_3=0$ and $B_0=1, B_1=0$, (c) $A_0=0, A_1=0, A_2=1, A_3=0$ and $B_0=0, B_1=1$ and (d) $A_0=0, A_1=0, A_2=0, A_3=1$ and $B_0=1, B_1=1$