Design of ultra compact 4:2 encoder using two dimensional photonic crystals

Jyoti B. Patil4 · Sanjaykumar C. Gowre1 · Mahesh V. Sonth2· Baswaraj Gadgay3

Received: 5 March 2022 / Accepted: 7 June 2022
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract
In this paper all optical ultra compact 4:2 encoder is proposed and designed using two dimensional photonic crystals (PC). The proposed structure has silicon rods of refractive index 3.4 embedded in air host by creating line defects in hexagonal lattice platform. The analysis of the design is done for various experimental values of radius, lattice constant and pitch values using finite difference time domain (FDTD) and plane wave expansion (PWE) method of licensed OptiFDTD software tool. The structure is optimised to get maximum power confinement at the output of the two ports of the 4:2 encoder by inserting extra rods which interns acts like a resonator to couple the power to the two output waveguides. The structure is chosen in such a way that ($\lambda$) will fall around 1550 nm wavelength only and is good for long distance transmission application as it is having low attenuation constant and high contrast ratio. Further, the proposed 4:2 encoder is operated at 1550 nm and it provides a high contrast ratio of 9.25 dB, propagation delay 33.1 fs and foot print of the structure is 119.34 $\mu$m². Hence it is highly advisable for photonic integrated circuits and optical signal processing.

Keywords Optical encoder · Nano resonator · Photonic crystals · Contrast ratio

Mahesh V. Sonth
maheshsonth@gmail.com
Jyoti B. Patil
jyotipati129@gmail.com
Sanjaykumar C. Gowre
sanjaygowre@gmail.com
Baswaraj Gadgay
baswaraj_gadgay@vtu.ac.in

1 ECE Department, Bheemanna Khandre Institute of Technology, Bhalki, Karnataka, India
2 ECE Department, CMR Technical Campus, Hyderabad, Telangana, India
3 VTU PG Centre, Kalaburagi, Karnataka, India
4 Present Address: Research Scholar, ECE Department, Bheemanna Khandre Institute of Technology, Bhalki, India

Published online: 29 August 2022
1 Introduction

In today’s communication network the prime aim is to accomplish ultra-fast transmission speeds. Hence all epistle steps on the network that is data transferring and processing information, should be executed in a full optical form (Salmanpour et al. 2015; Xavier et al. 2016). Photonic crystal (PC) is chosen as the suitable platform for designing optical devices because of its features such as lifetime, flexible design, good temperature resilient, low radiation loss and low group velocity Joannopoulos et al. (1997). The other platforms that are highly suitable for photonic integrated circuits are Planar Light wave Circuits (PLC), Phasmonics, Micro electro-optical-mechanical- systems (MEOMS) Rajasekar et al. (2020). Photonic crystal is an optical composition with two different materials combined in a single substrate to direct the signal of light into a nanostructure. Photonic crystal basic characteristic is its photonic band gap (PBG) concept by which the light property can be changed at an optical wavelength. The types of photonic crystals based on fabrication are 1D, 2D and 3D among which 2D PC is highly attractive because other optical devices can be easily integrated with it. Hence can be used efficiently to build various photonic devices such as logic gates Shaik et al. (2017), sensors (Rajasekar and Robinson 2018; Sonth et al. 2021), flip flops Soma et al. (2022), filters Ansari et al. (2021) and encoders (Alipour-Banaei et al. 2016; Mehdizadeh et al. 2017; Naghizade and Khoshsimia 2021; Gholamnejad and Zavvari 2017; Moniem 2016; Ouahab and Naoum 2016; Anagha et al. 2018; Soma et al. 2022). The encoders can also be designed using PC with some plasmon resonance effect by inserting GaAs and Gold rods into the dielectric Si rod structures. The sizes of this plasmon is comparatively smaller than the PC rods and they strongly interact with light and provide better resonance for localization of light into the resonance cavity Hamedi et al. (2021).

The confinement of light using phasmonics waveguides are better for reducing the power coupling and intern it will help in reducing the cross talk effect in long distance communication applications Haddadan et al. (2022). In Haddadan and Soroosh (2019) has designed 8 to 3 encoder without using cavity and resonators for coupling the power only 17 waveguides used for guiding the power from input to the output. In Haddadan et al. (2020) an 4 to 2 encoder is designed using waveguides, stacks and optical combiners for creating structure using 2D PC and normalized power achieved in this article is 46% for logic 1. The designing mechanism of photonic crystal based devices can be of three types. The first type is interference effect method. The second method is making use of materials having non-linear properties in nano resonators and ring resonators. The third method is self collimation effect. In a communication network the encoder is used to generate the binary code in analog to digital convertor. In literature all optical encoders are realized by using 2 dimensional photonic crystals with various techniques such as self- collimation Alipour-Banaei et al. (2016), the interference (Anagha et al. 2018; Mostafa et al. 2019) and non-linear effect (Rajasekar and Robinson 2018; Sonth et al. 2021). The encoders designed by self-collimation method requires phase shifters which results in to large foot prints so the cost of the device will be more.

The encoder designed by using nonlinear materials occupies less area which in turn reduces the cost of the devices. In Moniem (2016) the 4:2 encoder is designed by combining a T waveguide with four resonant rings and the designed encoder has a 1225 μm² of foot print and switching speed is 500 GHz. In Yang et al. (2017) the all optical 4 to 2 encoder was designed which is capable of working at mutual wavelengths by using...
nonlinear materials whose dimension is 240.5 $\mu m^2$ and Logic one power is 45% and logic zero power is 5% . In Mehdizadeh et al. (2017) the 4 to 2 encoder was realized by designing a buffer and OR gate which is capable of generating 2 bit binary code and overall footprint is 800 $\mu m^2$. The different optical encoders are designed by using different platforms like square lattice and hexagonal lattice by using photonic crystal ring resonators PCRR till date. The designed resonators are in the form of square, hexagon, ellipse and quasi square (Naghizade and Khoshsima 2021; Gholamnejad and Zavvari 2017; Moniem 2016; Ouahab and Naoum 2016; Anagha et al. 2018; Seif-Dargahi 2018; Mostafa et al. 2019; Hassangholizadeh-Kashtiban et al. 2015). These designed encoders need high input power to operate and resulted in to large footprints. In the present work a novel all optical encoder is proposed and designed with 2 nano resonators in the photonic crystal waveguides to reduce the radius of the rods to get all ultra-compact size and to obtain a equal output power in all states.

### 2 Basic 4:2 Encoder

The encoder executes the reverse operation of a decoder. It has $2^N$ inputs and N outputs as shown in Fig. 1. Only two values it can have at a time either on/off or 1/0. In a 4:2 encoder only one input is activated (logic 1) at a time and other inputs are inactivated (logic 0) and the equivalent binary coded output is received at the output ports depending upon selected active input line. The four binary inputs of an 4:2 encoder are [0001], [0010], [0100] and [1000] and its respective binary outputs are [00], [01], [10] and [11] which is clearly presented in the Table 1.
3 Structure of proposed optical 4:2 encoder

The proposed 4:2 optical encoder structure consists of $18 \times 18$ arrays that is 18 dielectric rods in x axis and 18 dielectric rods in z axis are used. The Si rods having refractive index $n=3.4$ in the air host with refractive index $n=1$ and designed in a hexagonal lattice. The proposed design consists of four inputs $I_0$, $I_1$, $I_2$ and $I_3$ ports, two outputs $O_1$ and $O_2$ ports and two nano resonators as shown in Fig. 2. The size of the structure is $11.7 \ \mu m \times 10.0 \ \mu m$. PWE method is used to calculate the photonic band gaps (PBG), in order to analyze the optical behavior of the structure. PBG is obtained to be $0.379 \leq (\frac{\alpha}{a}) \leq 0.599$ which wavelength range is $1065 \ \text{nm} \leq \lambda \leq 1683 \ \text{nm}$. $1550 \ \text{nm}$ the selected wavelength falls in this range. The band gap diagram is exploited for different values of $(\frac{\alpha}{a})$ and suitable values of $a$ and $r$ are selected. The value of lattice constant $a=638 \ \text{nm}$, $r$ (radius of the rod) $=112 \ \text{nm}$ and radius of nano resonators are chosen ($r_1$ and $r_2$) to be $58 \ \text{nm}$ and used to conjoin the light into the required output. The area of the proposed structure is $119.34 \ \mu m^2$. In order to get the high and equal power at output the nano resonators are chosen with a value of $58 \ \text{nm}$. The following Fig. 3 is the refractive index profile of the designed encoder. The band diagram of design is shown in above Fig. 4. The PWE method is used to determine the band gap of the design.

4 Operating principle of 4 to 2 optical encoder

All optical encoders are realized by using Gaussian continuous signals with an operating wavelength of $1550 \ \text{nm}$. As the ports $I_0$ to $I_3$ are used to input the light to the structure, we stimulate the structure by passing the light through one of the port at a time and examine the ports $O_1$ and $O_2$ as they are used to obtain the light out from the structure.
5 Case 1: \( I_0 \) port is active

The input power is applied to port \( I_0 \), and power applied in the other input ports are zero as shown in Fig. 5a. In this case both the output must be zero. Hence in case 1 according to the proposed structure the input does not find the way to the output ports \( O_0 \) and \( O_1 \) as the port \( I_0 \) waveguide is not connected to the output ports. Hence obtained output is almost equal to zero as shown in Fig. 5b and Figure 5c. In order to reduce the size of the structure, the port \( I_0 \) is chosen as a short-waveguide. Fig. 5b and 5c shows the output at observation point \( O_1 \) and \( O_2 \) are 0.03 and 0.06 respectively, which is almost equal to zero as shown in the Table 1.
6 Case 2: \( I_1 \) port is active

In this case \( I_1 \) port power is \( P_{in} \) and the power applied to the other ports are zero as shown in the Fig. 6a. When the input is applied, the maximum amount of the input power reaches the \( O_1 \) output port through the Nano resonator 1 as shown in Figure 6b and a small percentage of power passes to the \( O_2 \) output port as shown in Fig. 6c. The Table 2 shows the simulation results when \( I_1 \) is active.

7 Case 3: \( I_2 \) port is active

In this case \( I_2 \) port power is \( P_{in} \) and other ports power is zero as shown in Fig. 7a. When the input is applied, the maximum amount of the input power reaches the \( O_2 \) output port through the Nano resonator 2 and a small percentage of power passes to the \( O_1 \) output port as shown in the Fig. 7b and 7c.

8 Case 4: \( I_3 \) port is active

In this case \( I_3 \) port power is \( P_{in} \) and other ports power are zero as shown in Fig. 8a. When the input power is applied to the \( I_3 \) port, it reaches the \( O_1 \) and \( O_2 \) output ports through the nano resonator 1 and nano resonator 2 as shown in the Fig. 8b and 8c respectively.

Table 2 represents the summary of output obtained in all the four cases and we can cross verify the values with the Table 1. The Figure 9 represents the contrast ratio of designed encoder by varying the lattice constant. Initially the material Si is considered.
Fig. 6 Simulation result of case 2: $I_1$ port is active

(a) The electromagnetic field pattern when the input port $I_1$ is active

(b) Output at observation point $O_1$

(c) Output at observation point $O_2$

Fig. 7 Simulation result of case 3: $I_2$ port is active

(a) The electromagnetic field pattern when the input port $I_2$ is active

(b) Output at observation point $O_1$

(e) Output at observation point $O_2$
Fig. 8  Simulation result of case 4: \( I_3 \) port is active

**Table 2**  Practical In/Out of all-optical 4 to 2 encoder

| Case | Inputs \((P_{in}=1\text{ a.u.})\) | Outputs (a.u.) |
|------|---------------------------------|----------------|
| 1    | 0 0 0 0 \( P_{in} \)          | 0.06 0.03       |
| 2    | 0 0 \( P_{in} \) 0           | 0.059 0.473     |
| 3    | 0 \( P_{in} \) 0 0         | 0.515 0.060     |
| 4    | \( P_{in} \) 0 0 0         | 0.461 0.461     |

Fig. 9  Contrast ratio of optical 4:2 encoder with respect to lattice constant
Table 3  Comparison of the proposed optical 4 to 2 encoder results with previous work done so far

| References                          | Lattice structure | Material       | Contrast ratio (dB) | Dimension ($\mu m^2$) | Propagation delay |
|-------------------------------------|-------------------|----------------|--------------------|-----------------------|-------------------|
| Rajasekar and Robinson (2018)       | Square            | Si-BTO         | 7.84               | 3795                  | –                 |
| Mehdizadeh et al. (2017)            | Triangular        | Si             | 15                 | 880                   | 200 fs            |
| Naghizadeh and Khoshima (2021)      | Rectangular       | GaAs           | –                  | 1927                  | –                 |
| Cholamnejad and Zavvari (2017)      | square            | Si             | –                  | 1225                  | 1 ps              |
| Moniem (2016)                       | Square            | Si             | –                  | 240.5                 | 1.9 ps            |
| Ouahab and Naoum (2016)             | Hexagonal         | Si             | 5.7                | 218.2                 | –                 |
| Anagha et al. (2018)                | Square            | Si             | 9.2                | 130.6                 | –                 |
| Seif-Dargahi (2018)                 | square            | Si             | 9.2                | 174.24                | 1.8 ps            |
| Mostafa et al. (2019)               | Hexagonal         | Si             | 6                  | 128.5                 | 0.1 ps            |
| Hassangholizadeh-Kashtiban et al. (2015) | Rectangular     | Si             | –                  | 800                   | –                 |
| Makvandi et al. (2021)              | Square            | Si             | –                  | 133                   | 205 fs            |
| Hamedi et al. (2021)                | Square            | GaAs and Au    | –                  | 627                   | –                 |
| Present work                        | Hexagonal         | Si             | 9.25               | 119.34                | 33.1 fs           |
and varied the lattice constant by keeping the rod radius and radius of nano resonators constant and calculated the contrast ratio for different lattice constants. Secondly the material Ge is considered and varied the lattice constant by keeping the rod radius and the radius of nano resonators constant and determined the contrast ratio. From the Figure 9 it is clear that the proposed encoder gives good results with the Si material. From the Table 3, it is very clear that the proposed 4:2 encoder has high contrast ratio as well as small dimension. The contrast ratio for the 4:2 encoder is the logarithmic ratio of ON power level to OFF power level and the relation between free space velocity (C), frequency (f) and wavelength (λ) is given by

\[ C = f \times \lambda \]  
\[ C = \frac{\text{distance}(d)}{\text{time taken}(t_p)} \]  
\[ t_p = \frac{d}{f \times \lambda} \]  

So substituting all the values d=10 μm, f=1.946e+14 Hz and λ=1550 nm we will get propagation delay around 33.1 fs. An optical resonator (or resonant optical cavity) is an arrangement of optical components which allows a beam of light to circulate in a closed path.

Radius \( r = 58 \) nm, Length=10 μm, \( \epsilon_r = 3.4 \)

\[ f_{mnp} = \frac{1}{2\pi \sqrt{\mu \epsilon}} \sqrt{\frac{X_{mn}}{r}^2 + \left(\frac{p\pi}{L}\right)^2} \]  

The computations of resonance frequencies are
\( r \) and \( L \) are the cavity size in mm
\( m, n, p \) are the mode numbers excluding \( m=n=p=0 \)
\( X_{mn} \) value is extracted from Bessel functions as shown in Table 4.

\( f_{012} = 1.946e+14 \) Hz and \( \lambda = 1541 \) nm

### Conclusion

In the proposed design of all optical 4:2 encoder, utilizes the low input power as non-linear material is not used. The overall footprint of all-optical encoder structure is stingy and equal to 119.34 μm² and the contrast ratio obtained is 9.25 dB. The structure designed is very simple and compact and achieved comparatively better propagation delay around 33.1 fs with the existing literature. These amenities prompt it feasible to employ this 4 to 2 encoder in Photonic integrated circuits and optical computing.
Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Jyoti B], [Sanjaykumar C Gowre], [Mahesh V Sonth] and [Bassawaraj Gadgay]. The first draft of the manuscript was written by [Jyoti B] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding VGST, Bangalore, Karnataka State, India under award no. VGST/K-FIST (L1) (2014-15)/ (2015-16)/373 has supported this work.

Declarations

Conflict of interests The authors have no relevant financial or non-financial interests to disclose.

References

Alipour-Banaei, H., Rabati, M.G., Abdollahzadeh-Badelbou, P., Mehdizadeh, F.: Application of self-collimated beams to realization of all optical photonic crystal encoder. Physica E: Low-dimensional Syst. Nanostructures 75, 77–85 (2016)

Ansga, E., Rajesh, A., Saranya, D.: “Design of an all optical encoder using 2d photonic crystals.” In 2018 2nd International Conference on Inventive systems and control (ICISC), pp. 55–59, IEEE, (2018)

Ansari, J.N., Gowre, S.C., Sonth, M.V., Gadgay, B., Roy, A.S.: Photonic nano dielectric crystal cavity with infiltrated biosamples for refractive index sensing application. Integr. Ferroelectr. 213(1), 93–102 (2021)

Gholamnejad, S., Zavvari, M.: Design and analysis of all-optical 4–2 binary encoder based on photonic crystal. Opt. Quantum Electron. 49(9), 1–12 (2017)

Haddadan, F., Soroosh, M.: A new proposal for 4-to-2 optical encoder using nonlinear photonic crystal ring resonators. Inter. J. Opt.Photon. 13(2), 119–126 (2019)

Haddadan, F., Soroosh, M.: Low-power all-optical 8-to-3 encoder using photonic crystal-based waveguides. Photon. Netw. Commun. 37(1), 83–89 (2019)

Haddadan, F., Soroosh, M., Alaei-Sheini, N.: Designing an electro-optical encoder based on photonic crystals using the graphene-al 2 o 3 stacks. Appl. Opt. 59(7), 2179–2185 (2020)

Haddadan, F., Soroosh, M., Alaei-Sheini, N.: Cross-talk reduction in a graphene-based ultra-compact plasmonic encoder using an au nano-ridge on a silicon substrate. Appl. Opt. 61(11), 3209–3217 (2022)

Hamedi, S., Negahdari, R., Ansari, H.R.: Design plasmonic optical 4× 2 encoder based on 2d photonic crystal ring resonator. Plasmonics 16(6), 1983–1990 (2021)

Hassangholizadeh-Kashitiban, M., Sabbagh-Nadooshan, R., Alipour-Banaei, H.: A novel all optical reversible 4× 2 encoder based on photonic crystals. Optik 126(20), 2368–2372 (2015)

Joannopoulos, J.D., Villeneuve, P.R., Fan, S.: Photonic crystals: putting a new twist on light. Nature 386(6621), 143–149 (1997)

Makvandi, M., Maleki, M. J., Soroosh, M.: Compact all-optical encoder based on silicon photonic crystal structure. J. Appl. Res. Electrical Eng., 1(1), (2021)

Mehdizadeh, F., Soroosh, M., Alipour-Banaei, H.: Proposal for 4-to-2 optical encoder based on photonic crystals. IET Optoelectron. 11(1), 29–35 (2017)

Moniem, T.A.: All-optical digital 4× 2 encoder based on 2d photonic crystal ring resonators. J. Modern Opt. 63(8), 735–741 (2016)

Mostafa, T.S., Mohammed, N.A., El-Rabaie, E.-S.M.: Ultracompact ultrafast-switching-speed all-optical 4× 2 encoder based on photonic crystal. J. Comput. Electron. 18(1), 279–292 (2019)

Naghibzade, S., Khoshshima, H.: Low input power an all optical 4× 2 encoder based on triangular lattice shape photonic crystal. J. Opt. Commn. 42(1), 17–24 (2021)

Ouahab, I., Naoum, R.: A novel all optical 4× 2 encoder switch based on photonic crystal ring resonators. Optik 127(19), 7835–7841 (2016)

Rajasekar, R., Robinson, S.: Nano-electric field sensor based on two dimensional photonic crystal resonator. Opt. Mater. 85, 474–482 (2018)

Rajasekar, R., Raja, G. Thavasi., Jayabarathan, J.K., Robinson, S.: High speed nano-optical encoder using photonic crystal ring resonator. Photon. Netw. Commun. 40(1), 31–39 (2020)

Salmanpour, A., Mohammadnejad, S., Bahrami, A.: Photonic crystal logic gates: an overview. Opt. Quantum Electron. 47(7), 2249–2275 (2015)
Seif-Dargahi, H.: Ultra-fast all-optical encoder using photonic crystal-based ring resonators. Photo. Netw. Commun. 36(2), 272–277 (2018)
Shaik, E. Haq., Rangaswamy, N.: Investigation on photonic crystal based all-optical clocked d-flip flop. IET Optoelectron. 11(4), 148–155 (2017)
Soma, S., Sonth, M.V., Gowre, S.C.: Design of two-dimensional photonic crystal based ultra compact optical rs flip-flop. Photonic Netw. Commun. 43(2), 109–115 (2022)
Sonth, M.V., Soma, S., Gowre, S.C.: Investigation of light behavior of all optical full adders in two-dimensional photonic crystals. Microw. Opt. Technol. Letters 63(4), 1304–1308 (2021)
Xavier, S.C., Carolin, B.E., Kabilan, A.P., Johnson, W.: Compact photonic crystal integrated circuit for all-optical logic operation. IET Optoelectro. 10(4), 142–147 (2016)
Yang, Y.-P., Lin, K.-C., Yang, I.-C., Lee, K.-Y., Lee, W.-Y., Tsai, Y.-T.: All-optical photonic-crystal encoder capable of operating at multiple wavelengths. Optik 142, 354–359 (2017)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.