



Ultra-compact with improved data rate optical encoder based on 2D linear photonic crystal ring resonator

Mayur Kumar Chhipa¹ · B. T. P. Madhav¹ · Bhuvneshwer Suthar² · Vijay Janyani³

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Abstract

In the present work, a high-speed optical encoder is proposed based on two-dimensional photonic crystal ring resonator using coupled mode theory and resonance effect. Square-shaped ring resonator, couplings rods, and several waveguides have been utilized in the proposed structure. Silicon rods in air structure have been designed with rod radius of 0.1a and lattice constant 'a' as 540 nm. The photonic band gap is being calculated using plane wave expansion method and finite-difference-time-domain method to analyze the performance characteristics of optical encoder like transmission spectra, electric field view, contrast ratio, response time, etc. The operating wavelength of structure is 1550 nm, to perform encoder operation where only one input port is activated at a time while other input ports are inactivated, and accordingly equivalent binary encoded signal is produced at output ports. The proposed encoder is designed with fast response time 222.76 fs, high data rate of 4.48 Tbps, and ultra-compact size of 140.84 μm^2 . Hence the proposed device is suitable for high-speed optical computation as photonic integrated circuit.

Keywords Optical encoder · Bandgap structures · Defects · PHOTONIC crystal · Photonic crystal ring resonator · PWE method

1 Introduction

Integration of high-speed light devices, as well as technological advances, are critical factors influencing the development of integrated photonic circuits for optical communication networks. Every day, the increasing demand for wider bandwidth needs signal processing systems at high-speed. In conventional electronics, the signal processing speed is limited due to slow speed and huge power consumption. All-optical signal processing is an alternate way to increase signal processing speed at very low power consumption [1]. Using the new generation of optical devices to perform all-optical logic operations with rapid transfer, storage, high

processing speed, and high data rate, there are advantages to the realization of photonic integrated technology in comparison to the issues discussed in conventional electronic devices. Massive research is being conducted to design miniaturised photonic components for integrated circuits. In general, photonic integrated circuits (PICs), are the combination of various photonics technologies like Photonic Crystals (PCs), Plasmonic, Planar Lightwave Circuits (PLCs) and Micro-Optical-Mechanical Systems (MOEMS). In comparison to the above discussed different platforms for PICs, photonic crystals-based devices are preferred because of their various advantages like ultra-compact in size, more temperature resilient, flexible design structure, low radiation losses, high operation speed, and very low group velocity [2].

The photonic crystal (PC) structure is micro- or nano-scale in size with two kinds of dielectrics, made up to modulate the flow of light in a designed structure on a single substrate. Moreover, among various properties of PCs, photonic bandgap (PBG) due to a periodic structure has attracted attention, which is one of the key components for the implementation of PICs in controlling and guiding the flow of light [3].

✉ Bhuvneshwer Suthar
bhuvneshwer@gmail.com

¹ Department of Electronics and Communication Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram, Guntur, Andhra Pradesh 522502, India

² Department of Physics, M.L.B. Govt. College, Nokha, Bikaner 334803, Rajasthan, India

³ Department of Electronics & Comm. Engineering, Malaviya National Institute of Technology, Jaipur, India

Essentially, PC devices are designed to create defects such as point and line defects in order to localise and guide light within the device. Such structures could be one, two, or three-dimensional (3D), with two-dimensional (2D) PCs being particularly appealing due to their small size, high operating speed, low loss, and two-dimensional variation [2]. Based on 2D PC various devices have been designed such as waveguides [4, 5], optical sensors [6–8], optical filters [9, 10], multiplexer/demultiplexer [11–13], logic gates [14, 15], optical switches [16, 17], etc. The optical encoders can be designed with three different techniques: self-collimation [18], nonlinear effect [19, 20], and interference effect [21–24]. Among these three methods, the interference effect method along with coupled mode theory is utilized in this paper, as it can be designed with small dimensions and consumes less power in comparison to self-collimation method which requires phase shifters and is designed with large dimensions and also with nonlinear effect, which consumes high power with lower dimensions.

In the present work, a proposed structure consists of a square ring resonator along with 6 coupling rods that have placed to reduce counter propagation modes and four scatter rods placed on the corner of ring resonator to reduce the scattering loss, and designed to get fast response time and ultra-compact size. There are numerous methods, which can be utilized to analyze PCs, out of them finite-difference-time-domain (FDTD) method is utilized as it will allow us to obtain results quickly for a large variety of structures and allowing us to obtain highly accurate results in a fraction of the time. For simulation of PC structure, OptiFDTD simulation tool of Optiwave Systems Inc is utilized to observe transmission, contrast ratio, field view of electric field, response time. The plane wave expansion (PWE) method is used to calculate PBG, which helped in calculation of frequency bands for transverse magnetic (TM) and transverse electric (TE) modes [25–27].

Present work is structured as: in the next section, proposed design with the working principle of optical encoder along with this photonic band gap structure has been discussed. After that simulation results and analysis have been done along with various parameters of optical encoder as contrast ratio, response time and data rate in comparison to previous work done by various researchers around the world and improved results have been discussed. At last conclusion and future work possibilities are discussed.

2 Proposed encoder design and working principle

The proposed device using two-dimension photonic crystals (2D PhCs) of a square lattice structure with silicon (Si) rods embedded in air has been designed. The digital logic encoder

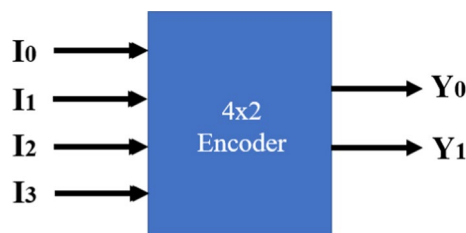


Fig. 1 A schematic of 4×2 optical encoder

Table 1 The 4×2 optical encoder truth table

Input Ports				Output Ports	
I3	I2	I1	I0	Y1	Y0
0	0	0	1	0	0
0	0	1	0	0	1
0	1	0	0	1	0
1	0	0	0	1	1

is a device that has 2^N inputs and gives outputs coded as N bits. Here, we study the 4×2 encoder, which has 4 inputs denoted by I0, I1, I2, and I3 along with 2 outputs denoted by Y0 and Y1, which is shown in Fig. 1 and truth table which contains its input and output values shown in Table 1. The proposed design contains four linear waveguides namely W1, W2, W3, and W4 and a square ring resonator. Out of these four linear waveguides, four waveguides are working as input waveguides for 4×2 optical encoder and among these four waveguides, two waveguides W2 and W4, as output waveguide, meeting at output port to Y1 and Y0. Proposed structure is a linear structure, where rod radius is $r=0.1a$ and lattice constant as $a=540\text{ nm}$ with dielectric constant of silicon as $\epsilon=12.04$.

The proposed structure parameters discussed in Table 2 have been optimized by review analysis on different design aspects as required for band gap calculation, optical integrated circuits, and optical encoder applications. Along with this, 6 coupling rods have been placed with rod radius of $r1=0.07a$ to reduce counter propagation modes and to reduce the scattering loss, four scatter rods have been placed on the corner of ring resonator with radius of $r1=0.03a$, as shown in Fig. 2. Such small rod size radius structured pattern of PCs can be designed by an electron beam lithography (EBL) technique. The patterns must be converted to the top of the silicon layer which use inductively coupled plasma (ICP) etching methods. [28].

2.1 Working principle

The spatial coupled mode theory (CMT) suggests [29], the amplitudes of waveguide mode for parallel waveguides are interconnected by the Eq. (1).

Table 2 Parameters used for the proposed optical encoder based on PCRR

Designing Parameters	Symbol	Value	Unit
Normalized bandgap (TE)	$1/\lambda$	0.535512–0.800032 1.33914–1.38646	μm^{-1}
Normalized bandgap (TM)	$1/\lambda$	1.56981–1.57602	μm^{-1}
Centre Wavelength	λ	1550	nm
Refractive index of dielectric rods	nr	3.47	–
Refractive index of background material	ns	1	–
Lattice Constant	a	540	nm
Dielectric rods' radius	r	0.1a	nm
Coupling rods' radius	r1	0.07a	nm
Scatter rods' radius	r2	0.03a	nm
Length of waveguide (W1)	W1	10.26	μm
Length of waveguide (W2 and W4)	W1/W4	11.34	μm
Length of waveguide (W3)	W3	3.78	μm
Footprint of the proposed structure	–	141	μm^2

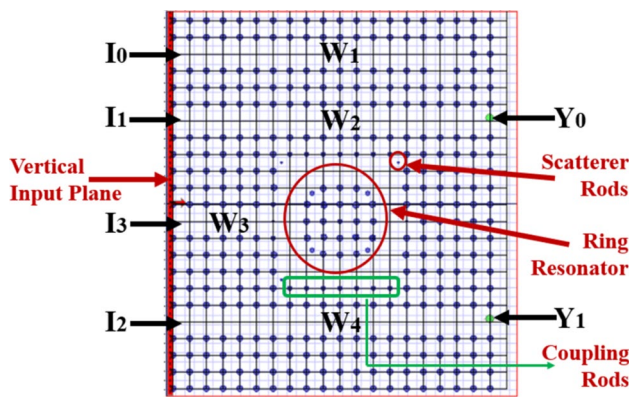


Fig. 2 Block diagram of 4×2 optical encoder

$$\begin{aligned} \frac{dA_1(z)}{dz} &= -j\beta_1 A_1(z) + \kappa_{12} A_2(z) \\ \frac{dA_2(z)}{dz} &= -j\beta_2 A_2(z) + \kappa_{21} A_1(z) \end{aligned} \tag{1}$$

where $A_{1,2}(z)$ is amplitude, $\beta_{1,2}$ is wave vector and κ is coupling coefficient. The conservation of energy suggests the coupling coefficients satisfies relation $\kappa_{12} = -\kappa_{21}^*$ [29]. Thus, the absolute value of coupling coefficient is $\kappa \equiv |\kappa_{12}| = |\kappa_{21}|$ [27]. Therefore, the propagation coefficients correspond to different modes are given in Eq. (2) as

$$k_{1,2} = \frac{\beta_1 + \beta_2}{2} \pm \sqrt{\left(\frac{\beta_1 - \beta_2}{2}\right)^2 + \kappa^2} \tag{2}$$

where propagation constant k_1 and k_2 correspond to odd and even mode. Using such modes [30, 31], the coupling length in two waveguides (parallel) is given in Eq. (3) as

$$L_c = \frac{\pi}{k_1 - k_2} \tag{3}$$

Using CMT, the coupling length of symmetrical parallel waveguide is given in Eq. (4) as

$$L_c = \frac{\pi}{2k} \tag{4}$$

The amplitude and intensity of propagation mode is function of distance traveled in waveguide (z) and coupling coefficient. So, the amplitude and intensity are expressed in Eq. (5&6) as

$$A_1(z) = A_0 \cos(kz) \text{ and } I_1(z) = A_0^2 \cos^2(kz) \tag{5}$$

$$A_2(z) = -iA_0 \sin(kz) \text{ and } I_2(z) = A_0^2 \sin^2(kz) \tag{6}$$

When the propagation distance is odd integer multiple of coupling length the input single is transferred from waveguide 1 to waveguide 2.

2.2 Photonic band gap analysis

The proposed design of 2D PC structure with Si rods embedded in air is designed with square lattice ring resonator. Here, PWE method is used to obtain PBG of proposed design in cases of TE and TM modes discussed in Table 2. It has been observed that the effective value of refractive index provides a good 3D simulation approximation, as for passive structure, two-dimensional is preferred and three-dimensional for sensors.

It is shown in Fig. 3 that two band gaps are existing in TE modes. First photonic bandgap exits from 0.535512 to 0.800032 on wave number scale (μm^{-1}) or 1249.9 nm to 1867.3 nm on wavelength scale, while second photonic band

from 1.33914 to 1.38646 on wave number scale (μm^{-1}) or 721.2 nm to 746.7 nm. It is shown also in Fig. 3b that one small band gap is existing in TM modes photonic bandgap exits from 1.56981 to 1.57602 on wave number scale (μm^{-1}) or 634.5 nm to 637.0 nm in wavelength scale. First photonic bandgap is quite wide with width of 617.4 nm and exits in infrared region, which has good application in optical communication and networks. So, this designed structure with Si material can be utilized for photonic integrated circuits and device application.

3 Results and discussion

Here, we calculated electric field view, transmission, contrast ratio and response time using FDTD method. The resonant wavelength is 1550 nm for different encoder operations, input ports are I0, I1, I2, and I3 from where input light signal is launched and Y0 and Y1 are two output ports, where light signal is received. While observing the transmission, the logic operation states are considered, as output power is above 0.35 is taken as logic ‘1’ and output power is below 0.3 is taken as logic ‘0’. Here, 4×2 optical encoder is designed and simulated. For the proposed encoder, four different cases have been studied, and accordingly designed structure has been simulated and performance has been analyzed.

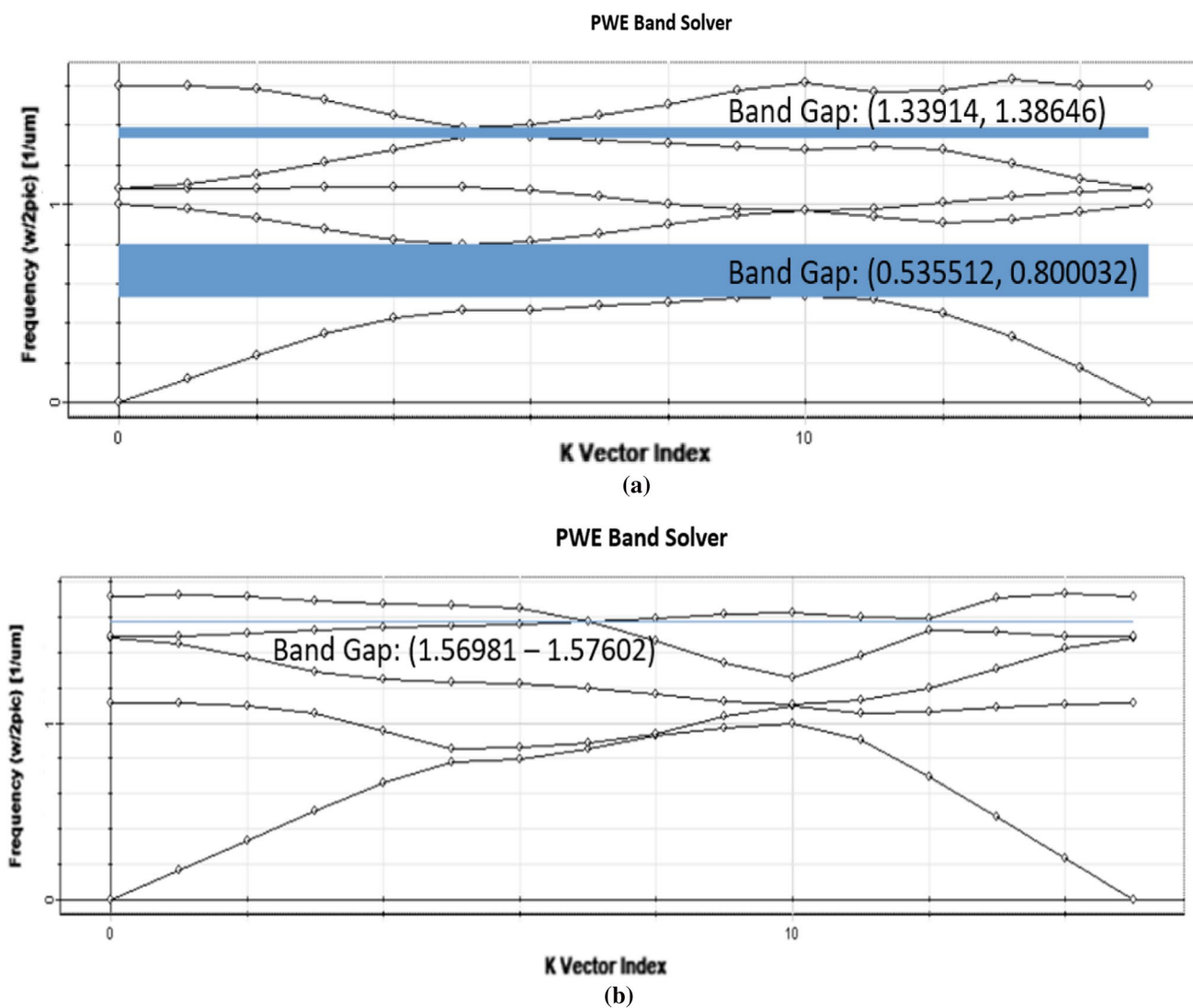


Fig. 3 PBG structure of 2D PC-based silicon rods in air structure **a** PBG in TE mode and **b** PBG in TM mode

Case 1: $I_0 = 1$ and $I_1 = I_2 = I_3 = 0$, optical light is launched at input port I_0 and it travels through optical waveguide W_1 . The separation of three rows of rods between optical waveguide W_1 and waveguide W_2 causes weak coupling between these waveguides. As a result, the maximum signal is only transmitted into waveguide W_1 , and only a small portion of the input signal couples to waveguide W_2 , and the signal does not reach at output ports Y_0 and Y_1 , as illustrated in Fig. 4b. The output power at Y_0 is 0.16, while at Y_1 is 0.06 as illustrated in Fig. 4a. So, the optical encoder follows $Y_0 = Y_1 = 0$ (OFF) condition.

Case 2: $I_1 = 1$ and $I_0 = I_2 = I_3 = 0$, the optical light is launched at input port I_1 and it travels through optical waveguide W_2 . The separation of two rows of rods between optical waveguide W_2 and ring resonator cause weak coupling of signal from waveguide W_2 to ring resonator. As a result, the maximum signal is only transmitted into waveguide W_2 and only a small portion couples to ring resonator, resulting maximum part of the signal reaching at port Y_0 and only small portion reaching at port Y_1 as illustrated in Fig. 5b. The power at output port Y_0

is 1.38, while at port Y_1 is 0.09 as illustrated in Fig. 5a. Therefore, the optical encoder follows $Y_0 = 1$ (ON) and $Y_1 = 0$ (OFF) condition.

Case 3: $I_2 = 1$ and $I_0 = I_1 = I_3 = 0$, the optical light is launched at input port I_2 and it travels to optical waveguide W_4 . The separation of two rows of rods between optical waveguide W_4 and ring resonator cause weak coupling of signal from waveguide W_4 to ring resonator. As a result, the maximum signal transmitted into waveguide W_4 and a small portion couples to ring resonator, resulting in maximum signal received at port Y_1 , while a small portion reaches output port Y_0 as illustrated in Fig. 6b. The power at output port Y_0 is 0.08, while at port Y_1 is 1.3 as illustrated in Fig. 6a. Therefore, the optical encoder follows $Y_0 = 0$ (OFF) and $Y_1 = 1$ (ON) condition.

Case 4: $I_3 = 1$ and $I_0 = I_1 = I_2 = 0$, the optical light is launched at input port I_3 and it travels to optical waveguide W_3 . At the start point of ring resonator, the input signal splits into two equal parts and travel in ring resonator in opposite direction. As the coupling rods are present on the both side of ring resonator, which causes strong coupling from ring to optical waveguide W_2 and W_4 . As a result, the

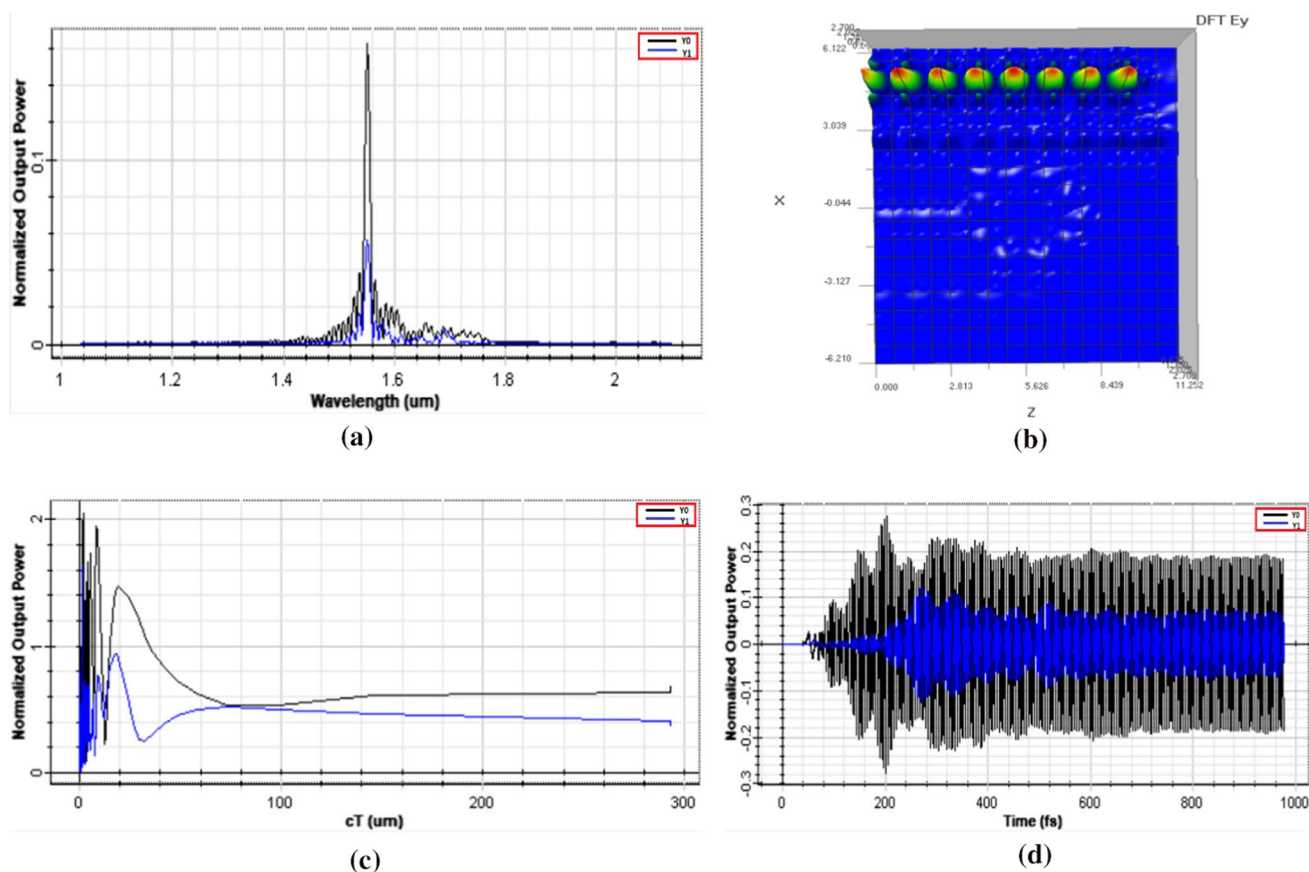


Fig. 4 a Transmission spectra, b Optical signal distribution of inputs 1000, c Normalized output power of inputs 1000, d The output power level of inputs 1000

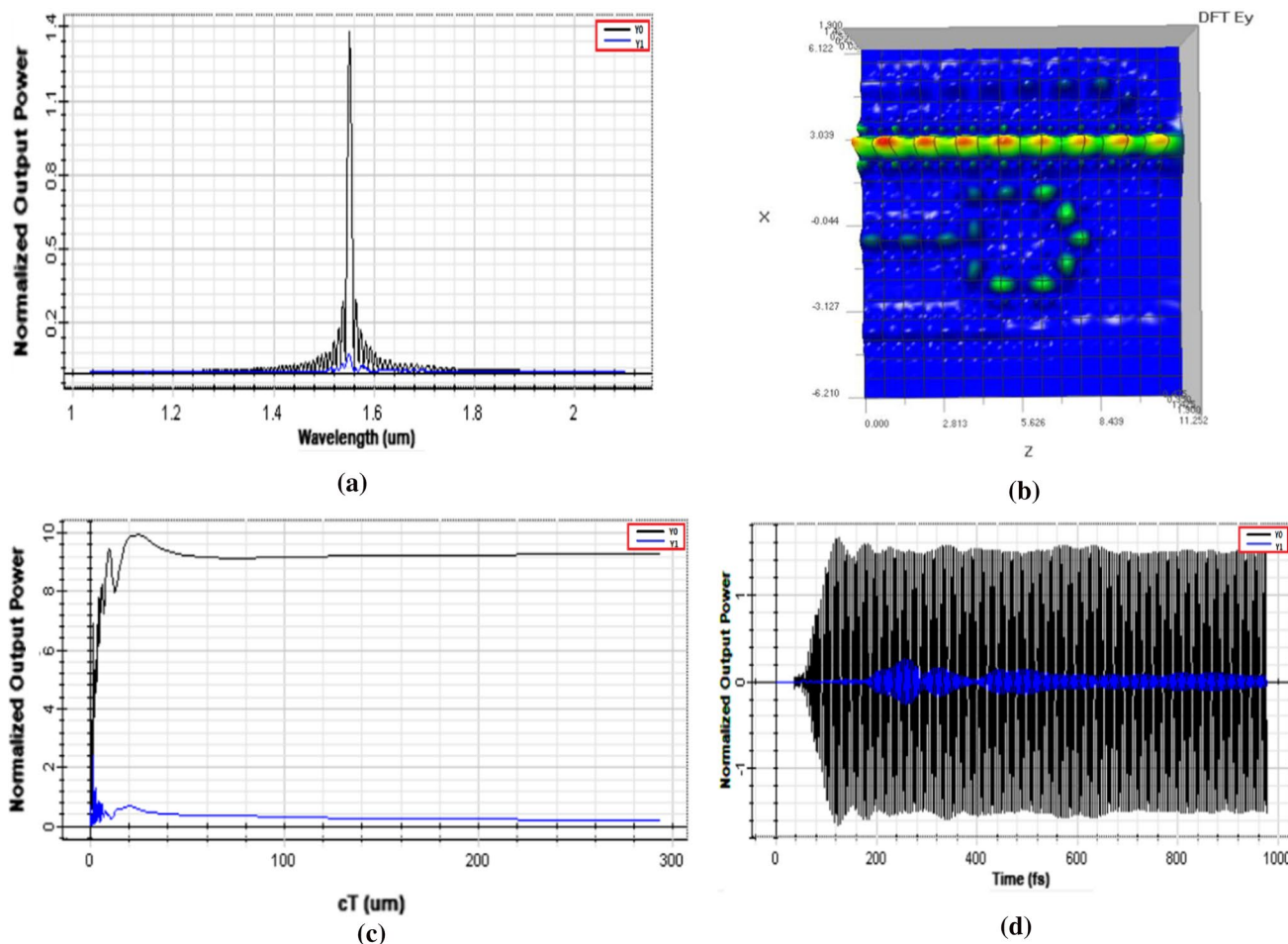


Fig. 5 **a** Transmission spectra, **b** Optical signal distribution of inputs 0100, **c** Normalized output power of inputs 0100, **d** The output power level of inputs 0100

single is received at both ports Y0 and Y1, consequently as illustrated in Fig. 7b. The power at port Y0 is 0.53, while at port Y1 is 0.57 as illustrated in Fig. 7a. Therefore, the optical encoder follows $Y0 = Y1 = 1$ (ON) condition.

3.1 Contrast ratio

The most important parameter to examine the efficiency of all-optical devices is the contrast ratio. The optical encoder's Contrast Ratio (CR) is described as the ratio of output power and it can be computed using equation (7)

$$CR(dB) = 10 \log \left\{ \frac{P1}{P0} \right\} \tag{7}$$

where P0 is power for the logic '0' and P1 power for logic '1' output power.

For the input condition when I1=1 (0100), the output power level at Y0 is 1.38 and Y1 is 0.06 as it is shown in Fig. 5a, correspondingly its CR is 11.85dB. In similar way,

for input condition when I2=1 (0010), the output power level at Y0 is 0.08 and Y1 is 1.3 as it is shown in Fig. 6a, the calculated CR is 12.10 dB. For the other two cases 00 and 11 of encoder, output response of these logic states are same as it equally distributed, so for these two conditions, CR is not calculated.

3.2 Response time and data rate

Apart from contrast ratio (CR), the other important parameter is propagation response time and data rate, need to be calculated for logic devices. The data rate is defined as reciprocal of response time. As shown in the normalized curves in Figs. 4–7c, d, the data rate and response time have been calculated theoretically.

For input condition when I0 = 1 (1000), both response time and data rate cannot be calculated, as the power at both output ports is below 0.3 and output logic is 00. For the input condition when I1 = 1 (0100), the output port

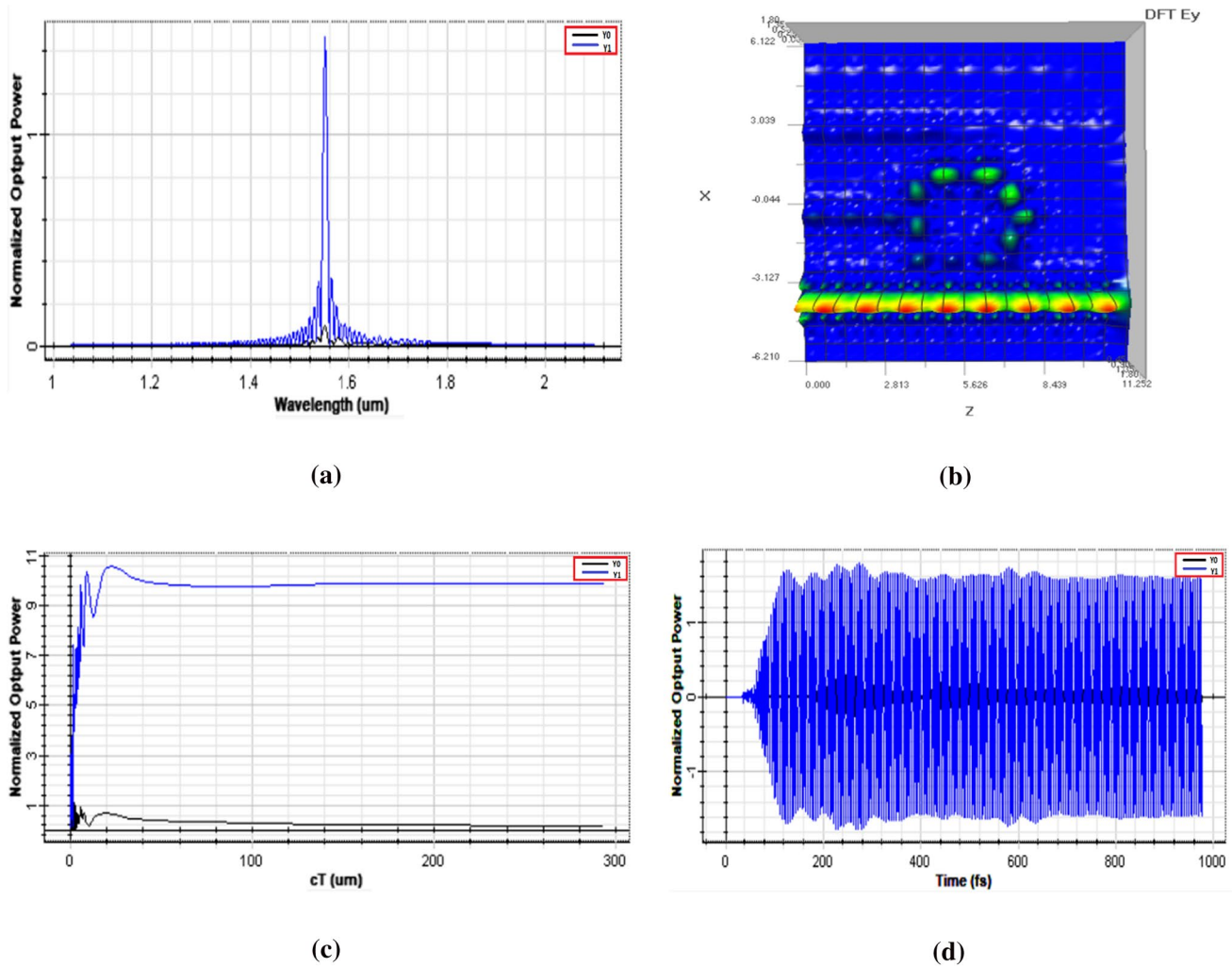


Fig. 6 **a** Transmission spectra, **b** Optical signal distribution of inputs 0010, **c** Normalized output power of inputs 0010, **d** The output power level of inputs 0010

logic is 10 ($Y_0=1$, $Y_1=0$), results response time as $cT = 22.59 \mu\text{m}$ and its corresponding the response time is 86.37fs, while data rate is 11.57Tbps from Fig. 5c, d. For the input condition when $I_2=1$ (0010), the output port logic is 01 ($Y_0=0$, $Y_1=1$), results in the response time as $cT = 22.79 \mu\text{m}$ and its corresponding response time is 89.78 fs while data rate is 11.13Tbps from Fig. 6c, d. For the input condition when $I_3=1$ (0001), the output port logic is 11 ($Y_0=1$, $Y_1=1$), results in response time as $cT = 29.76 \mu\text{m}$, and its corresponding value is 222.76 fs while data rate is 4.48Tbps from Fig. 7c, d. The complete performance of the 4×2 encoder is displayed in Table 3.

It is being observed from Table 2 that the maximum response time is observed as 222.76 fs, the minimum value of contrast ratio is found as 11.85 dB and the minimum observed data rate is 4.48 Tbps, respectively.

3.3 Scatter rod radius analysis

Scatter rod radius analysis is done in this proposed encoder, where four scatter rods have been placed at inner corners of resonator. From the simulation, it has been observed that these scatter rods influence the efficiency of proposed encoder. For optimization, different radius of scatter rods is observed from $0.025a$ to $0.035a$ (13 nm to 18 nm), with a range of 1 nm. In comparison with different scatter rod radius analysis as shown in Table 4, with 16 nm scatter rod radius, encoder has provided optimum power and good contrast ratio for all the logic states of 4×2 encoder.

The performance of the present optical encoders is calculated and compared to previous work of many researchers around the world and is presented in Table 5. The comparative parameters are contrast ratio (CR), response time

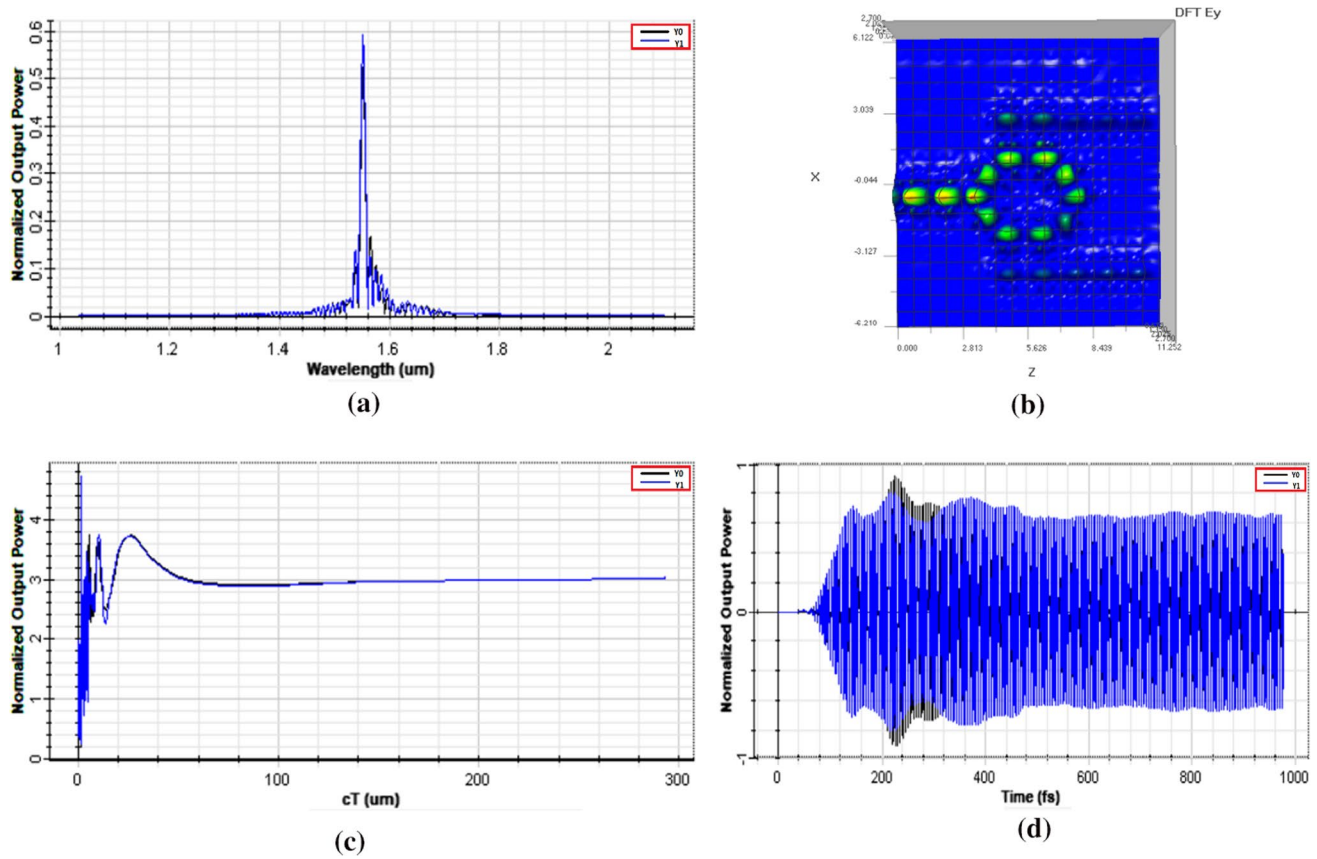


Fig. 7 **a** Transmission spectra, **b** Optical signal distribution of inputs 0001, **c** Normalized output power of inputs 0001, **d** The output power level of inputs 0001

Table 3 The various input and output parameters of 4×2 optical encoder

Input Ports				Output Ports		Contrast Ratio (dB)	Response Time (fs)	Data Rate (Tbps)
I3	I2	I1	I0	Y1	Y0			
0	0	0	1	0.06	0.16	–	–	–
0	0	1	0	0.09	1.38	11.85	86.37	11.57
0	1	0	0	1.3	0.08	–	89.78	11.13
1	0	0	0	0.57	0.53	12.10	222.76	4.48

Table 4 Contrast ratio analysis with scatter rod radius for the 4×2 encoder

S. No	Scatter Rod Radius (nm)	Contrast Ratio (dB)
1	13	11.83
2	14	12.05
3	15	12.04
4	16	12.10
5	17	12.04
6	18	12.07

and footprint of designed encoder. One of the research paper authored by Sei-Dargahi [22] shows higher dimensions of $795.6 \mu\text{m}^2$, with low response time of 1.8 ps. In another paper by Anagha et al. [23] shows the minimum footprint of $218.2 \mu\text{m}^2$, where output power is 0.75 W. The proposed encoder by Naghizada et al. [28] shows higher dimensions of $625 \mu\text{m}^2$, but reflects minimum response time of 0.7 ps. However, our proposed optical encoder achieved high contrast ratio (11.85 dB), fast response time (222.76 fs), high data rate (4.48 Tbps), and

Table 5 Comparative analysis with previously designed optical encoder

References	Encoder Type	Lattice Structure	Defects	Dimensions (μm^2)	Contrast Ratio (dB)	Response Time (ps)
Alipour-Banaei et al. [18]	4×2	Hexagonal	Line and Point defects	3795	7.84	1.4
Iman et al. [19]	4×2	Square	Ring Resonator	240.5	–	–
Gholamnejad et Al. [20]	4×2	Hexagonal	Ring Resonator	1927	–	1
Rajasekar et al. [21]	4×2	Square	Ring Resonator	174.2	12.86	0.369
Seif-Dargahi [22]	4×2	Square	Ring Resonator	795.6	9.2	1.8
Anagha et al. [23]	4×2			218.2	5.7	1
Naghizade et al. [32]	4×2	Square	Line and Point defects	625	15	0.7
Moniem [33]	4×2	Square	Ring Resonator	1225	–	1.9
Proposed Work	4×2	Square	Ring Resonator	140.8	11.85	0.222

ultra-compact size ($140.84\mu\text{m}^2$). With the above parameters, it is observed that the present device can be used for high-speed optical computations.

4 Conclusions

We proposed a design of a 4×2 optical encoder based on a two-dimensional photonic crystal ring resonator, where dielectric rods are made up of silicon material with a rod radius is $r = 0.1a$ and lattice constant ‘a’ as 540 nm. The properties of the proposed optical encoder are investigated and simulated with the FDTD method and the PWE method for PBG analysis. The resonance and coupled mode theory played an important role in designing the encoder. When an input signal is launched from I3, input terminal to waveguide W3, it gets split into two equal parts and travels in the ring resonator in opposite direction. As the coupling rods are present on both sides of the ring resonator, which causes strong coupling through the ring to optical waveguides W2 and W4. The contrast ratio is 11.85 dB, with response time of 0.222 ps, switching speed of 4.48 Tbps, and ultra-compact size of $140.84 \mu\text{m}^2$. Further analysis could be done for different operating wavelengths and other parameters such as modifying the radius of rods, scatter rod radius or lattice constant. Such a device structure with low power consumption, small size and high data rate, which occupy less space could be utilized in future as photonic integrated circuits for high-speed optical communication.

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Declarations

Conflict of interest No conflict of interest.

Consent to participate Informed to all authors.

Consent for publication Asked all authors for submission.

Ethical approval Not Applicable.

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Mayur Kumar Chhipa is Research Scholar at the department of Electronics and Communication Engineering, K L Deemed to be University (Koneru Lakshmaiah Education Foundation) Vaddeswaram, Guntur, Andhra Pradesh, India. He received his B. Tech and M. Tech degrees from Rajasthan Technical University in 2011 and 2015, respectively. He is the author or coauthor of more than 20 research papers in reputed journals and conference proceedings. He has attended about 20 workshops and organized 2 workshops. He is a member of IEEE, IEEE Photonic Society, OSI and IAENG. His current research interests are in the areas of Band Gap Structures, Optical Communication, Photonic Crystals, Photonic Integrated Circuits, Optical Devices, and Optical Networks.



Dr. B.T.P. Madhav was born in India, A.P, in 1981. He received the B.Sc, M.Sc, MBA, M.Tech degrees from Nagarjuna University, A.P, India in 2001, 2003, 2007, and 2009 respectively. He received his PhD in the field of antennas from K L University in 2015. From 2003–2007 he worked as lecturer and from 2007 to 2011 he worked as Assistant Professor and from 2011 to 2015 he worked as Associate Professor and from Aug–2015

he is working as Professor in Electronics and Communication Engineering. He has published more than 190 papers in International, National journals and Conferences. He is reviewer for several international journals including Elsevier and Taylor and Francis and served as reviewer for three international conferences. His research interests include antennas, liquid crystals applications and wireless communications. He is a life member of ISTE, IACSIT, IRACST, IAENG, UACEE and fellow of IAEME. He is the editorial board member for 15 journals. He is acting as Sub-Editor for IJST.



Dr. Bhuvneshwer Suthar was born in 1983 in Bikaner, India. He received a B.Sc. degree in 2002 from MDS University, Ajmer, India and an M.Sc. degree in Physics in 2004 from the University of Bikaner, and a PhD degree in Photonics in 2011 from MGS University, Bikaner (formerly the University of Bikaner). He received the Junior Research Fellowship of CSIR, New Delhi, India during 2006–2008 and the Senior Research Fellowship of CSIR, New Delhi, India during 2008–2011. He has worked

as an Assistant Professor in the College of Engineering & Technology, Bikaner during 2011–2012 and then in Govt. Engineering College, Bikaner during 2012–2018. At present, he is working as an Assistant Professor in the Department of Physics, MLB Government College, Nokha, Bikaner, India. He has published more than 45 research papers in national and international-level journals and also published more than 35 papers in various international conference proceedings. He has published two authored books and two edited books on photonic crystals in Nova Science Publishers, Inc. (USA) and CRC Press, UK. He has been worked an editor of four international conference proceedings published in AIP Conference Proceedings, USA. His research interests include Optoelectronics, Photonics, and Nonlinear Optics.



Dr. Vijay Janyani is a Professor in Department of Electronics and Communication Engineering (ECE) at Malaviya National Institute of Technology (MNIT) Jaipur. He obtained B.Engg and M.Engg degrees from MREC (now MNIT), and PhD from University of Nottingham, UK under Commonwealth Scholarship. In his teaching and research career of more than two decades, he has been Investigator of a number of funded

research projects (both national and international) in the area of Optical Communication and Photonics, sponsored by reputed organisations like DRDO, DST, JSPS, SERI etc. He has published more than 180 research papers in reputed journals and conferences, and a number of book chapters. He has been member of Technical Program Committee of many IEEE conferences, and reviewer or editorial board member of reputed journals like IEEE/Elsevier/IET/Springer/Hindawi. He is a Senior Member of IEEE USA, Member of IEEE Photonics Society,

Member of IEEE COMSOC, IEEE NTC, Life Fellow of the Optical Society of India (OSI-India), Life Fellow of Institution of Engineers (India), Senior Member of OSA (USA), Senior Member of SPIE (USA) and Life Fellow of Institution of Electronics and Telecommunication Engineers (IETE) India. His current research interests include fiber optics and communication, photonics, optical networks, numerical modeling, nonlinear photonics, photonic crystal based photovoltaic and devices and all-optical systems.