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Ultra compact, high contrast ratio all optical NOR gate using two dimensional photonic crystals

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An all-optical NOR gate is implemented using a two-dimensional photonic crystal waveguide. The paper provides a structure of an all-optical NOR gate constructed by introducing a line and point defect. The proposed NOR gate uses a hexagonal lattice structure with E shaped waveguide. The contrast ratio, response time and bit rate of three input NOR gate are 29.59 dB, 0.8 ps and 1.19 Tbps, respectively. The proposed gate is constructed with the operating wavelength of 1550 nm. The structure has been simulated and analyzed using Finite Difference Time Domain (FDTD) and Plane Wave Expansion (PWE) methods. It offers high contrast ratio, better response time with ultra-compact size. Hence it is suitable for high speed optical integrated circuits and switching devices.

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Keywords: Photonic crystal, Optical logic gates, Photonic band gap, waveguide, NOR gate, Plane wave expansion

1. Introduction

Photonics communication is one of the advanced technologies which create a tremendous impact nowadays. To overcome the limitation of speed and security issues researchers gave more attention in optical communication technology. All optical logic devices play a vital role in designing Photonic Integrated Circuits [1]. Optical logic gates are the essential one in high speed telecommunication and they can be used in optical signal processing functions such as addressing, multiplexing/demultiplexing and switching applications. A high speed optical logic gates provides a solution for the increasing demand for high bandwidth [2]. Photonic Crystal is composed of periodic dielectric or Metallo-dielectric nanostructures that have alternate low and high dielectric constant materials. It has three types based on its direction of dielectric constant variation, such as, one, two and three dimensional Photonic Crystal. Among all, Two Dimensional Photonic Crystal is most widely used as it supports better confinement of light, easy to control the propagation of light and easy calculation of band gap and etc. A photonic bandgap (PBG) is a range of photon energies (or wavelengths) in which the propagation of electromagnetic waves, particularly light, is completely forbidden within a certain periodic structure or material. In essence, it is the optical analog of an electronic bandgap in a semiconductor. Mainly the optical devices are designed by 2D photonic crystal, such as, Encoders, Decoders [3-6], Adders [7-8], Multiplexers and Demultiplexer [9-11], add drop filter [12-13], Power splitter [14], Directional coupler [15], logic gates [16], Switches[17],sensors [18] and etc.

Logic gates are the basic building block of digital circuits. Logic gates are used in microprocessor and microcontroller applications. A combinational logic circuit is a circuit whose outputs only depend on the current state of its input [2]. In the literature, so far, there are several attempts made to realize logic gates using square and triangular lattices. Generally, the logic gates were designed through ring resonator [19] and defects based structures [1] with different mechanisms, such as semiconductor optical amplifier [20], Mach Zehnder Interferometer [21], self-collimation [22], multimode interference-effect [23] and etc. The performance parameters, namely, normalized output power, response time, bit rate and contrast ratio, were investigated.

An all optical XOR and OR logic gates were investigated using the line and point defect using a square lattice with an operating wavelength of 1550 nm and a delay time of 0.4ps [24]. Aryan Salmanpour et al. reported all optical photonic crystal NOT and OR logic gates using non-

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linear Kerr effect using a Ring Resonator in square lattice structure. While using the Kerr effect based non-linear material the signal dropped inside the waveguide and the normalized efficiency is low. Non-linear rods are made up of silicon photonic crystals with an extinction ratio of -18.7dB and bit rate of 333 Gbps [25]. An all optical NAND & NOR gate realized by introducing the Y shaped defect in square lattice structure constructed by Hassan Mamnoon- Sofiani et al. The functional parameters calculated as delay time for NAND/NOR gate are 2.5 ps and 1.5 ps, respectively, the footprint of the reported structure as 988 μm^2 [26]. A NOR gate implemented in an all-optical configuration comprises two nonlinear ring resonators positioned on top of a shared waveguide, and it functions at a high bit rate of 138.9 Gbps [27]. A non-linear Kerr effect based NOR and NAND gate photonic crystal constructed by using a cubic lattice structure which offers better response time as 2.5 ps [28].

T Shaped NOR gate designed with the square lattice operated with wavelength of the 1550 nm [29]. All optical NOR gates are constructed by using a ring resonator structure with a response period of 0.388 ps, a contrast ratio of 8.98 dB and 7.88 dB [30]. To increase the contrast ratio ultra-compact all optical NOR gate was designed with line and point defect using square lattice. The footprint of the NOR gate is 90.31 μm^2 [31]. Using a Plasmonic waveguide an all optical XOR, OR and NOT gate was constructed with an extinction ratio of 27.80 dB [32]. Preeti Rani et al. realized an all optical logic gate using a triangular lattice structure. It operates with a wavelength of 1550 nm [33]. Pirzadi et al. was proposed an ultra-accurate and compact all optical hexagonal shaped ring resonators based structure for OR gate with 7.27 dB contrast ratio and bit rate of 0.8 Tbps. The reported OR gate was realized with a single line defect [34]. Tamer S. Mostafa et al. constructed a all optical AND/OR logic gate which investigated with a functional parameters such as a high bit rate of 6.76 and 4.74 Tbps, contrast ratio of 9.74 dB and 17.95 dB, respectively [35].

Golnaz Tavakoli et al. investigated the compact and fast XOR/XNOR gate based photonic crystal by cascading the two nonlinear ring resonators, using a nonlinear rod with the Kerr coefficient inside the PCRR. The maximum delay time are 1.5ps and 2.5 ps respectively [36]. Mohammad Reza Geraili et al. constructed a ring resonator based OR/NOT/AND gate using the square lattice structure by introducing the non-linear ring resonator. The quality factor of the resonant ring is 800 and it operates with the wavelength of 1500 nm [37]. Jayson k Jayabharathan et al. reported an all optical AND/OR logic gate. The functional parameters calculated such as contrast ratio 17.40 dB and response period as 0.92ps [38]. Alok kumar, Sarang Medhekar et. al designed a NOT and NOR gate PC based ring resonator offers a better contrast ratio and response time [39]. F. Parandin , M. M. Karkhanehchi et. al investigated the Terahertz all-optical NOR and AND logic gates operated with a bit rate of 1.54 Tbit/s [40]. Yuhei Ishizaka, Yuki Kawaguchi, Kunimasa Saitoh, Masanori Koshiba et. al designed a all-optical XOR and AND logic gates with low power consumption gate [41].

PCRR Based Bandpass Filter for C and L+U Bands of ITU-T G.694.2 CWDM Systems investigated by Robinson et. al. [42]. A novel polymer-based ring-core circular photonic crystal fiber (C-PCF) is proposed by Bibhatsu Kuiri, et. al. The detailed experimental feasibility and design sensitivity are theoretically addressed in this work [43]. Bibhatsu Kuiri et. al designed a loss polymer-based photonic crystal fiber supporting 242 OAM modes and its optimized in the band 1.5 THz to 3.5 THz [44].Wan Kuang et.al proposed a FDTD method for Non-orthogonal Unit-Cell Two-Dimensional Photonic Crystals [45]. W. J. Kim et. al investigated a finite element analysis of photonic crystal devices with respect to low loss modulator [46]. All optical AND gate based on Kerr effect proposed by Ehsan Veisi et. al. The design offers a better performance minimum contrast ratio, the response time, and the total area of the structure are 11.04 dB, 1.8 ps, and 194.56 μm2, respectively [47].

A two dimensional photonic crystal based logic gates investigated with the interference effect. Asmaa et al. made an new attempt on all type of gate such as AND, OR, NOR, NAND, XOR and NOT logic gates. The logic gate realized in one configuration with small footprint as 97.2μm^2 [48]. Meng et.al reported a AND/OR gate based on two dimensional photonic crystal. The functional parameter such as response time as 2.42 ps and extinction ratio of AND gate noted as 8dB [49]. A triangular lattice based NOR logic gate constructed with two optical signals, to achieve high logic state at zero input condition. The reported gate has been implemented as logic inverter and the noise margin calculated as 630 μW^2 using the maximum product criterion [50]. Koudded Elhachemi et.al investigated a logic gate function based properties aiding photonic crystal. A new hybrid platform of gallium arsenide and barium titanate (GaAs- BTO) for ultra efficient electro optic tuning introduced in the reported logic gates [51, 52]. An all optical AND/NAND and OR/NOR logic gate designed with high non Kerr non linearity [53, 54]. By applying the electric field the material properties also changed [55, 56].

From the above literature analysis, it is investigated that the functional parameters of the existing structure offers minimum response time and low contrast ratio. The footprint of the structure becomes too large. In order to minimize the footprint of the structure and to attain the minimum response time and high contrast ratio, the proposed NOR gate is designed. In this reported work, the proposed structure is constructed with a hexagonal lattice using 2DPC. The functional parameters such as contrast ratio, bit rate, response time and normalized efficiency are accounted.

The rest of the paper is organized as follows; Section 2 includes the design of the proposed three input NOR gate and its simulated results. Section 3 presents the simulation and results, and Section 4 represents the conclusion.

2. Three Input NOR Gate

The proposed all-optical three input NOR logic gate contains 21×21 hexagonal lattice embedded with silicon rods. The lattice constant of the proposed structure is, a=580nm, radius of rod is noted as r=0.11μm. Chalcogenide glasses have been known as optical materials which offer a wide transparency range, low optical losses, ultrafast response time, large linear/non-linear refractive index and stability to atmospheric moisture. It is used for optoelectronics, integrated optics, and photonics. In this attempt, the Chalcogenide glass with the refractive index of 3.46 is employed in this attempt [57]. To minimize the footprint of the structure and to reduce the power loss the line and point defect are introduced, in the proposed attempt.

Fig. 1 shows the band diagram for the proposed logic gate before creating the defects. The Plane Wave Expansion (PWE) method is used to obtain the band structure. The band diagram Transverse Electric (TE) PBG and Transverse Magnetic (TM) PBG. The PBG region for TE mode varies from $0.323<a/\lambda<0.494$ which is equal to 1364 nm$<\lambda<$1795 nm. Similarly, the TM PBG is calculated from $0.892<a/\lambda<0.983$ which is equal to 590 nm$<\lambda<$650 nm. Here, the first TE PBG is considered for this structure.

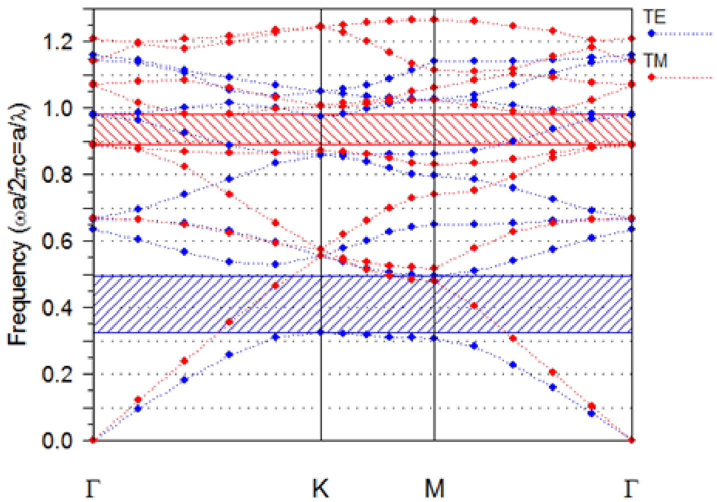

Fig. 1. Band diagram of PC based structure.

The schematic representation of three input NOR gate is shown in Fig. 2. It contains three input ports (Port A, Port B and Reference input) and one output port (Port Y). A circular ring resonator is introduced into the waveguide. The radius of the rod are optimized through parametric analysis in such a way that to obtain the maximum performance. The top of the waveguide is called a bus waveguide and the bottom of the waveguide is called a drop waveguide. The structure incorporated a waveguide by removing a rod column. A ring resonator was then formed within this structure by decreasing the rod's radius and adjusting the refractive index of the rod at specific positions. The outer and inner rod radii were varied in conjunction with the refractive index and rod size to optimize the normalized efficiency.

The radius of the outer rod is 50 nm and the refractive index of the outer rod is 3.46. The radius of the outer rod is shown in green and light cyan colour and the inner rod shown in Magenta colour (See in Fig.2). The radius of the inner rods is 50 nm (Yellow color), 60 nm (Magenta color) and 100 nm (Green color) which are optimized to obtain maximum efficiency.

The Finite Element Method (FEM) used for numerically solving differential equations. FDTD one of the most powerful tools used in nano-scale optical devices. The finite difference time domain method used for studying the propagation of light in a wide variety of photonic structures. FDTD algorithm allows for a wide range of simulation and analysis capabilities. It increases the speed and efficiency and it has the advanced capabilities for clustered simulation environment while comparing with FEM. It is an highly sophisticated tool for studying the propagation of light in a wide variety of photonic structures including integrated and fiber optic waveguide devices. It includes the Perfectly Matched layer (PML), periodic and symmetric/asymmetric boundary conditions.

Though there are various methods used to analyze the Photonic Crystal based optical devices, in order to meet the demands required for PC device PWE (Plane Wave Expansion) and FDTD (Finite Difference Time Domain) methods are used.

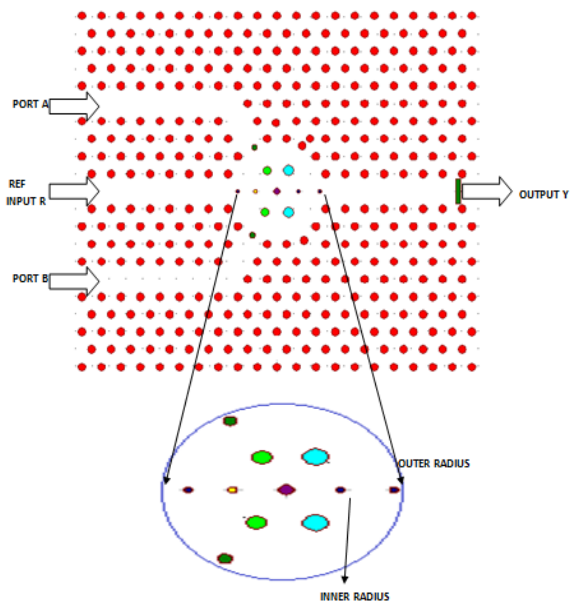

Fig.2. Schematic structure of proposed three input NOR gate.

PWE method:

Photonic Bandgap and propagation modes identified with help of band structure of photonic crystal. The band diagram obtained through PWE method. It includes electric and magnetic fields and the periodic dielectric structure is expanded in Fourier series.

The band diagram calculations of electric field are carried out by solving Maxwell's equation (master equation) which is

$$\nabla \times \left(\frac{1}{\varepsilon(r)} \nabla \times E(r)\right) = \frac{\omega^2}{c^2} E(r) \tag{1}$$

where '*c'* is the speed of light, 'ω' is the angular frequency, *ε(r)* is the dielectric constant (relative permittivity) and *E(r)* is the electric field of the periodic function. Because of the periodic 2DPC, the dielectric constant, ε can be described as

$$\varepsilon(r) = \varepsilon(r + R) \tag{2}$$

where, R is the vector of the 2D lattice.

FDTD method:

FDTD computes E and H field components at points on a grid with grid points spaced Δx, Δz. The time is broken up into discrete steps of Δt. The electric field components are computed at times t= nΔt and magnetic field at times t= (n+1/2) Δt, where 'n' is the integer representing computing step. In these PBG structure the propagation of EM waves efficiently investigated using the FDTD method. The FDTD method is a solution to Maxwell's equation and does not have any approximations and restrictions. Hence this method most widely used as a propagation solution technique in integrated optics and is also Maxwell's curl equation.

$$E_x\Big|_{i,j}^{n+1} = E_x\Big|_{i,j}^{n} + \frac{c\Delta t}{\varepsilon_0}\left[\frac{H_z\Big|_{i,j+1/2}^{n+1/2} - H_z\Big|_{i,j-1/2}^{n+1/2}}{\Delta y}\right] \tag{3}$$

$$E_y\Big|_{i,j}^{n+1} = E_y\Big|_{i,j}^{n} - \frac{c\Delta t}{\varepsilon_0}\left[\frac{H_z\Big|_{i+1/2,j}^{n+1/2} - H_z\Big|_{i-1/2,j}^{n+1/2}}{\Delta x}\right] \tag{4}$$

$$H_z\Big|_{i,j}^{n+1/2} = E_z\Big|_{i,j}^{n-1/2} + \frac{c\Delta t}{\mu_0}\left[\left(\frac{E_x\Big|_{i,j+1/2}^{n} - E_x\Big|_{i,j-1/2}^{n}}{\Delta y}\right) - \left(\frac{E_y\Big|_{i+1/2,j}^{n} - E_y\Big|_{i+1/2,j}^{n}}{\Delta x}\right)\right] \tag{5}$$

where the index 'n' denotes the discrete time step, indices 'i' and 'j' denote the discretized grid point in the X-Y plane.

The input signal is given to three input ports as A and B and the reference input, the output achieved in port Y for different logic functions. The given input and output power are determined by using time monitor and the transmission power is calculated by using the following equation as

$$\mathrm{T(f)} = \frac{1/2 \int \mathrm{real}\,(\mathrm{p(f)}^{\mathrm{monitor}})\mathrm{dS}}{\mathrm{Source\ Power}} \tag{6}$$

where T(f) is a signal power, dS indicates a surface normal, and p(f) Poynting vector. The FDTD method separates the electric or magnetic fields into time and space by Maxwell's equation. The FDTD method satisfies the following equation [9]

$$\Delta \mathrm{t} \le \frac{1}{\mathrm{c}\sqrt{\frac{1}{\Delta \mathrm{x}^2} + \frac{1}{\Delta \mathrm{z}^2}}} \tag{7}$$

where Δt indicates step time, and Δx and Δz are grid sizes in X-Z axes. The Perfectly Matched Layer (PML) is placed and it acts as the absorbing boundary condition to diminish optical loss in turn providing excellent performance.

3. Simulation Results and Discussion

Table 1 shows the truth table for NOR logic gate. It is examined that the output logic 0 when any one of the input and all inputs are ON and the output is '0', if all input is 'OFF'

Table 1. Truth table of three input NOR gate.

INPUT A	INPUT B	REFERENCE INPUT	OUTPUT
0	0	1	1
0	1	1	0
1	0	1	0
1	1	1	0

Figs. 3 (a-d) shows the time response and electric field distribution for four different logic levels(a) A=0, B=0,R=1 and Y=1 (b) A=0,B=1,R=1 and Y=0, (c) A=1,B=0,R=1 and Y=0, (d) A=1,B=1,R=1 and Y=0.The input signal which is applied in four cases

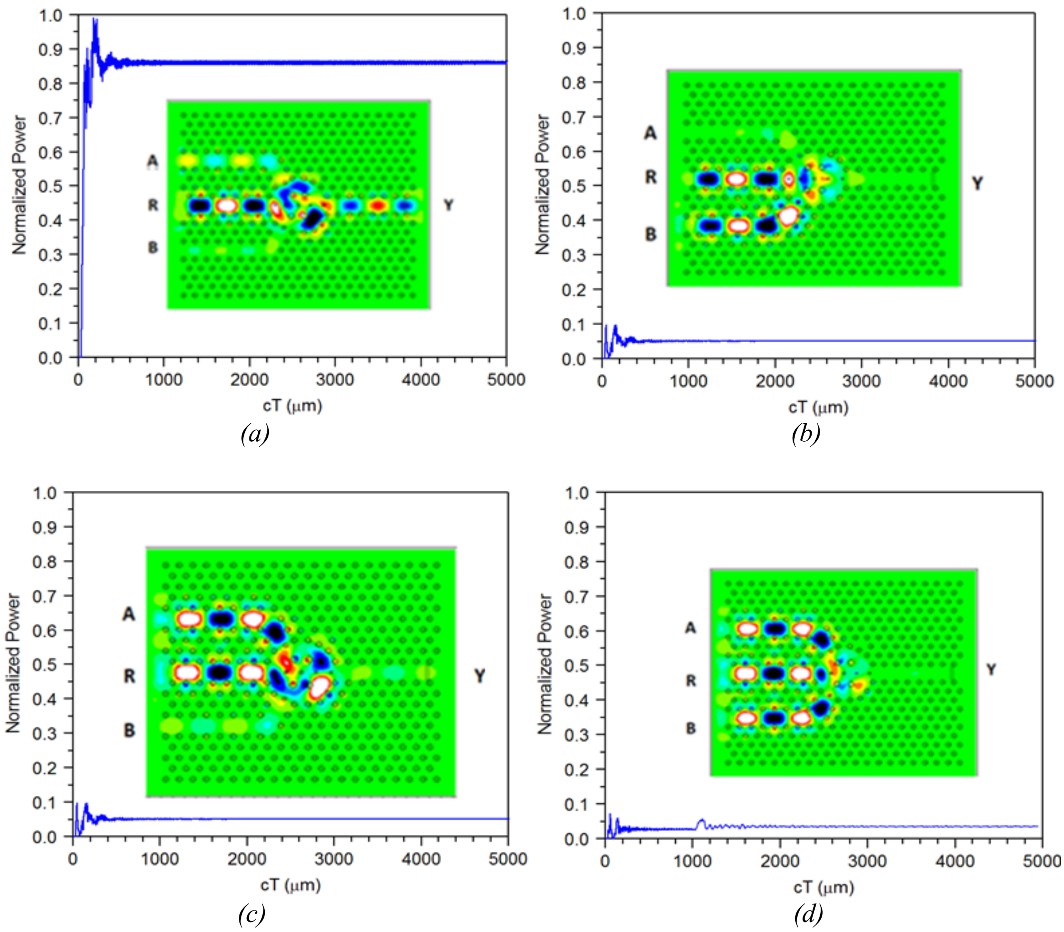

Fig. 3. Signal propagation of three input NOR gate (a) A=0,B=0,R=1 and Y=1 (b) A=0, B=1,R=1and Y=0, (c) A=1,B=0,R=1 and Y=0, and (d) A=1,B=1,R=1 and Y=0.

CASE 1: When both inputs are OFF and the reference input is ON, i.e., A=0 and B=0, R=1 then the Gaussian input signal passed inside the waveguide structure and the maximum amount of power 86% reached at the output port as shown in Fig. 3(a).

CASE 2: When any one of the input is ON, i.e A=0, B=1,R=1 the signal is coupled inside the waveguide of circular ring resonator and the output attained as 0.When the reference input R and the second input B is on ON condition, the minimal amount of power propagates inside the structure. The graphical response for the corresponding state is represented in Fig. 3(b) and the power reached at the output port is very minimal, as the signal reflected back to the input port.

CASE 3: Based on the logic applied in truth table in case 3 the reference input R and input A are on ON state condition, due to the existence of point and line defect the Gaussian input applied to both R and A there is minimal amount of power received at the output port. The corresponding electric field distribution for the logic 110 is depicted in Fig. 3(c).

CASE 4: Based on the logic applied in truth table in case 4 the all optical inputs such as input A, input B and input R are all in ON state condition, due the refractive index of the material and size of the rod there is no power coupled inside the defect which is represented in Fig. 3(d).Due to the defect there is minimal amount of power reached at the output port as 0.001%.

Fig.3 depicts the output response curve for three input NOR gate. The blue colour represents the output power (transmission efficiency) of the corresponding logic such as 001,011,101,111.

The contrast ratio defined as the logarithmic ratio of ON/OFF conditions. The logic 1 and logic 0 implies ON/OFF state conditions. The formula for CR stated as

$$C = 10\, log * (P_{ON}/P_{OFF}) \quad (8)$$

where P ON is the maximum output power at logic 1 and P OFF is the minimum output power at logic 0.

The response time is calculated from the transmission efficiency. The average power can be measured from 10% of output power and 90% of output power. The response time is calculated from the average power t2. The formula for calculating the response time as

$$R = 4t2 \quad (9)$$

where, t2 is the transmission delay response time.

Bit rate is an essential parameter in all optical logic gates and digital devices. It can be calculated as the response time inversely proportional to that of the transmission delay.

$$Bt = 1/Response\ time \quad (10)$$

The bit rate is measured in terms of Tbps. It depends on the response time, however, when the contrast ratio increased the response time drastically reduce.

Table 2. Logic input, Output level, Output power, Response time, Contrast ratio and Bit rate of the proposed three input NOR gate.

Input A	Input B	Ref Input	Output Y	Pout/Pa	Response Time (a)	Contrast Ratio (b)	Bit Rate (c)
0	0	1	1	0.91	0.8ps	29.59 dB	1.19 Tbps
0	1	1	0	0.01			
1	0	1	0	0.01			
1	1	1	0	0.001			

From the literature analysis most of the structural design uses a square lattice and the footprint of the structure too large and it offers low contrast ratio. In order to enhance better contrast ratio, bit rate and response time and to make the device compact the proposed gate constructed. While comparing with all other existing logic gates, it is clearly noticed that in photonic crystal based ring resonator structure, the Gaussian input power scattered over the waveguide. Due to the excessive amount of power coupled inside the ring resonator the minimum amount of power reached at the output port. In order to overcome these problems, the proposed gate constructed using the line and point defect based structure. Initially, the line and point defect based structure which reduces the power scattering inside the waveguide amount of power reached at the output port. Meanwhile the functional parameters investigated such as response time, bit rate and contrast ratio. In this reported work, the speed of operation of NOR gate determined by calculating the response time. While compared with all other existing logic gates the reported work produces better contrast ratio and response time.

Table 3. Comparison of functional parameters of the proposed NOR gate with reported gates.

Authors	Logic Gate	Lattice	Defect/ Mechanism	Power for output 0	Power for output 1	Contrast Ratio	Bit Rate	Size	Response Time
P.Andalib et.al 2009[27]	NOR	Cubic	Ring resonator	***	***	8.2 dB	138.9 Gbps	***	***
Pirzadi M et al. 2015[34]	OR	Hexagonal	Ring resonator	0.00	0.8	7.27 dB	0.8 Tbps	200 μm^2	***
Golnaz Tavakoli etal.2019 [36]	XOR/XNOR	Hexagonal	X shaped point defects	0.5	0.95	***	666 Gbps 400 Gbps	***	1.5 ps 2.5 ps
F.Parandin et al.2017 [40]	NOR &AND	Hexagonal	E shaped point defects	0.23	0.58	***	1.54 Tbps	***	0.65ps
Yuhei Ishizaka et al. 2011 [41]	XOR &AND	Hexagonal	X shaped line defects	***	***	6.79 dB	***	112 μm^2	***
Haraprasad Mondal et.al, 2022[50]	NOR	Hexagonal	Y shaped point defects	***	***	8.5 dB	***	850 μm^2	***
Proposed work	NOR	Hexagonal	E shaped defect with ring resonator	0.001	0.91	29.59 dB	1.19 Tbps	129.32 μm^2	0.8 ps

***- Not discussed

The functional parameters of the proposed NOR gate is compared with reported all optical logic gates and it is listed in Table 3. It is noticed that the contrast ratio is 29.59 dB which is better than the other reported gates as the power difference between logic 1 and logic 0 is high. In addition, the bit rate (1.19 Tbps) and response time 0.8 ps is also superior than the existing works. The size of the gate is compact when compared to all other reported gates. Hence the proposed NOR gate can be suitable for high speed switching photonic networks.

4. Conclusion

In this attempt, all-optical NOR gates based on two dimensional photonic crystals operated with a wavelength of 1550 nm is investigated. In order to obtain high optical intensity the line and point defect based ring resonator is introduced in the proposed structure. The structural and functional parameters are analyzed through Plane Wave Expansion method and Finite Difference Time Domain method. The contrast ratio, response period and bit rate of three input NOR gate are 29.59 dB, 0.8 ps and 1.19 Tbps, respectively. The footprint of the structure is about 129.32 μm^2. Hence this all optical NOR logic gate is suitable for optical integrated circuits and high speed switching networks.

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