International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING
ISSN :2147-6799 www.ijisae.org Original Research Paper

An Ultracompact All Optical Two-Dimensional Photonic Crystal Based and Gate

Rama Prabha Krishnamoorthy, Abdul Rahman bin Senathirajah, Robinson Savarimuthu, Abdul Rahim Sadiq Batcha

Submitted: 14/11/2022 **Accepted**: 16/02/2023

Abstract*:* An all optical logic gate which plays an important role in high speed switching networks. In this paper aim to construct and analyze the two-dimensional photonic crystal all optical AND gate. A logic gate is the basic building blocks of any digital system. The reported all optical AND gate is composed of two input waveguide and one output waveguide with line and point defect using a hexagonal lattice. The functional parameters such as contrast ratio, bit rate, transmission efficiency and response time are calculated. The performance of the AND gate is analyzed by using Finite Difference Time Domain method. The proposed logic gate is designed to operate at a wavelength of 1550nm. It offers high contrast ratio and minimum delay time. Hence it is suitable for photonic computational integrated circuits.

Keywords*: Photonic crystal, Ring Resonator, logic gates, Photonic band gap, Silicon*

1. Introduction

This Photonic crystal based logic gates which play a vital role nowadays in optical communication. In order to overcome the limitation of speed and security issues and Due to high transmission of data and high speed signal processing researchers gave more attention in designing all optical photonic integrated circuit [1].Logic gate are the basic building blocks of digital circuit. Therefore designing an efficient and compact low power and high frequency optical devices is essential one. [2-3].

Some several techniques are introduced in two dimensional photonic crystal based logic gates as Mach Zehnder Interferometer [4], Semiconductor Optical amplifier [5], Multimode interference waveguides [6-7] Self collimated beam [8]. By using these mechanisms there are many optical devices designed in two dimensional photonic crystal as adders [9], multiplexers, [10-11], demultiplexers [12-13], encoders [14], decoders [15], power splitter [16] and sensors [17,18]apart from these devices able to design an switches [19], add drop filter[20,21]. Logic gate consists of two inputs and one output. The PC has some special characteristics like low power consumption, high speed, compactness and it is flexible to design an integrated device.

Enaul haq Shaik et. al reported a T shaped waveguide AND gate without using non linear materials. It offers a bit rate of 6.26 Tbps and contrast ratio of 5.74dB. An ultra compact all optical XOR & AND gate constructed with the various functional parameters [22]. In order to reduce the power consumption the reported gate designed by Yuhei Ishizaka [23]. Parisa Andalib et al designed a Ultracompact AND gate based on nonlinear ring resonators [24]. Mohammed Danie et.al proposed a non linear Kerr effect based AND gate with a minimum delay time of 0.4 ps and the footprint of the structure about less than 100μm^2 [25]. An all optical AND gate operated with multiple wavelength such as 1.30, 1.43, 1.45, 1.49, 1.51, 1.55 μm [26]. Majid Ghadrdan et.al investigated an optical half adder by using AND & XOR logic gate based on nonlinear photonic crystal. The functional parameters such as contrast ratio of 12.78dB for AND gate and 5.67 dB for XOR gate were calculated. A T shaped waveguide introduced inside the half adder structure indium phosphide and chalcogenide glasses are used in this reported half adder [27]. An ultra high bit rate all optical AND/OR logic gates based on photonic crystal designed by Tamer S Mostafa et.al. I shaped waveguide created inside the structure by using a square lattice structure [28].

The rest of the paper is organized as follows; the band diagram of the proposed design is presented in section 2. The structural design of 2 input AND gate and its simulation results are discussed in Section 3.The design and results of 3 input AND gate is presented in Section 4.The Section 5 illustrates the

Department of Electronics and Communication Engineering Mount Zion College of Engineering and Technology Pudukkottai, India
ramaprabhakrishna8@gmail.com
Faculty of Business and Communications,INTI International University, Malaysia.
arahman.senathirajah@newinti.edu.my
Department of Electronics and Communication Engineering Mount Zion College of Engineering and Technology Pudukkottai, India
mail2robinson@gmail.com
Department of Electrical & Electronics, Faculty of Engineering & Built Environment MAHSA University Jenjarom, Malaysia
abdulrahim.b@mahsa.edu.my

conclusion.

1. Structural Design of and Gate

The proposed all optical AND logic gates contains 21×21 hexagonal lattice embedded in silicon rods. The structure mainly comprises by using a line and point defect based ring resonator. The structural parameters such as lattice constant a=600nm and radius of rod noted as r=0.12µm. The refractive index of the proposed AND gate structure is 3.6 (Silicon).

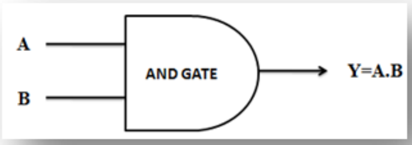


Fig. 1 Symbol of AND gate

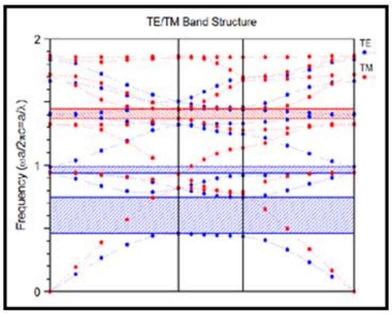


Fig. 2 Band diagram of the proposed structure design without defects

Fig. 2 shows the band diagram for the proposed logic gate before creating the defects. The Plane Wave Expansion method used to calculate the band structure. The band diagram gives the propagation mode and Photonic Band Gap (PBG) of the proposed structure. The proposed all optical AND gate has a transverse electric field (TE) and transverse magnetic field(TM) PBG. The band diagram shown below Figure 2 has both TE PBG and TM PBG where the blue color indicates TE PBG and red color represents TM PBG. The first TE PBG is obtained between 0.5492nm < (a/λ) < 0.540nm whose corresponding wavelength range.

2. Structure of Two Input and Gate

An all optical AND gate has two input ports as Port A and Port B and the output port noted as Y. There are two waveguide such as top and bottom of the waveguide. In order to attain maximum output power the refractive index and radius of the rod will be varied in the hexagon shaped ring resonator based structure. The line and point defects are introduced into the bus and drop waveguide.

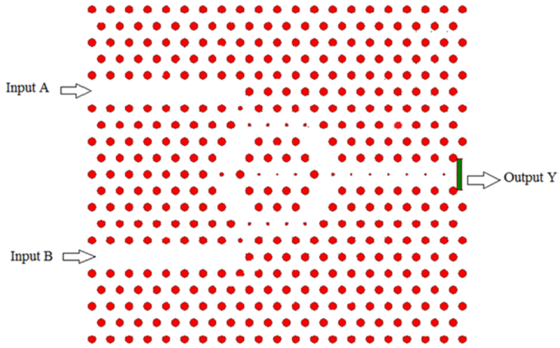


Fig. 3 Proposed two input AND gate structural design

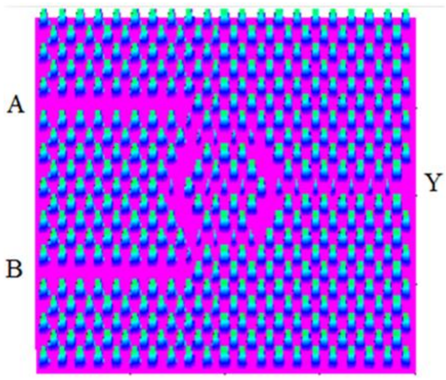


Fig. 4 3D view for the proposed two input AND gate

Fig. 3 shows the proposed two input AND gate. The radius and refractive index of the rod varied to attain maximum power and to increase the efficiency.

The 3D view of the proposed AND gate is shown in Fig. 4. When the signal is launched into the waveguide, the normalized efficiency is calculated by varying the properties of time monitor and its respective time response curve is plotted.

TABLE 1 Truth table of two input AND gate

INPUT A	INPUT B	OUTPUT Y
0	0	0
0	1	0
1	0	0
1	1	1

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

Where T(f) is a normalized signal power as function of frequency, dS denotes surface normal, and p(f) is Poynting vector. The FDTD method is separated the electric or magnetic fields into time and space by Maxwell's equation. The following equation will be satisfied by the Finite difference

Time Domain method.

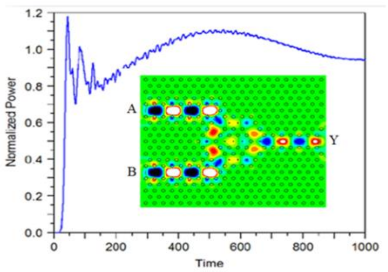
$$\Delta t \le \frac{1}{c\sqrt{\frac{1}{\Delta x^2}+\frac{1}{\Delta z^2}}} \tag{2}$$

Where Δt indicates step time, and Δx and Δz is grid size in X-Z axes.

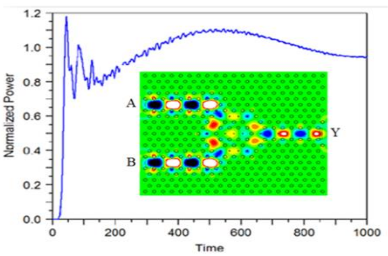
CASE 1: When both inputs are OFF condition i.e., A=0 and B=0, the signal is not coupled inside the waveguide so there was no output power in the output ports.

CASE 2: When anyone of the input is ON i.e., A=1 and B=0, the Gaussian input signal was not propagated inside the structure and the output not attained in output port.

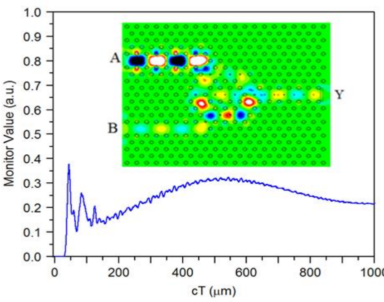
- CASE3: When one input is ON i.e., A=0 and B=1, the input power is applied to the port A and it enter into the waveguide there was no power coupled inside the waveguide and the output not achieved in port Y.
- CASE 4: When both inputs are ON i.e., A=1 and B=1, the input signal is launched into Port A and Port B which is propagated inside the structure, then the power reached at the output port.



(a)



(b)



(c)

Fig. 5 signal propagation for proposed two input AND gate as (a) A=1, B=1, Y=1, (b) A=0, B=1, Y=0 and (c) A=1, B=0, Y=0

Fig. 5 (a) to 5 (c) shows the electric field distribution and output response curve of the proposed two input AND gate for three different logics (11, 01 & 10).

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

Where P_1 is the power at logic 1 and P_0 indicates the power at logic 0.

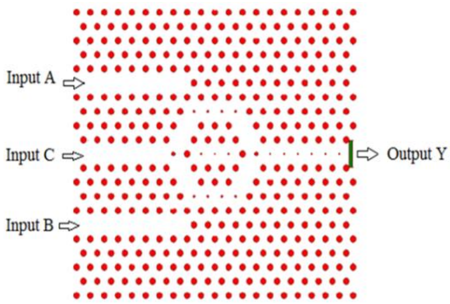
The output response of the AND gate is shown in above Fig. 5 represents the functional parameters such as contrast ratio, response time and bit rate. It offers better functional parameters such as contrast ratio 39.88 dB. The average output power is calculated that the time required traveling the output power from 0 % to 90 % output. The time consists of two components namely t and t_1 where t is the transmission delay to reach 0.1 % of P_{avg} and t_1 is the transmission delay to reach 90 %of P_{avg}. The response time calculated as 1.499 ps.

TABLE 2 FUNCTIONAL PARAMETER OF TWO INPUT AND GATE

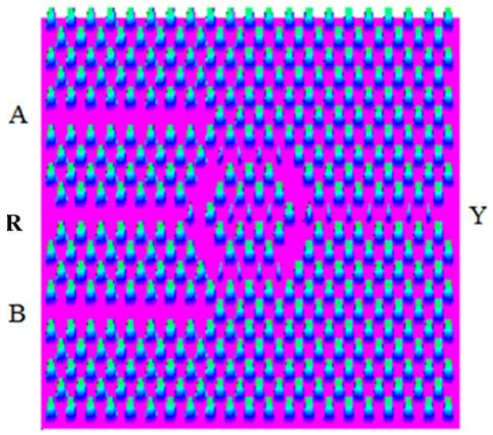
Input A	Input B	Output Y	Response time	Contrast ratio	Bit rate
0	0	0	1.499 ps	39.88 dB	0.666 Tbps
0	1	0			
1	0	0			
1	1	1			

3. Three Input and Gate

The proposed Y shaped defect based ring resonator extended for three input AND gate. The three input AND gate comprises of three input and one output ports. The reference port added in between the two input ports.



(a)

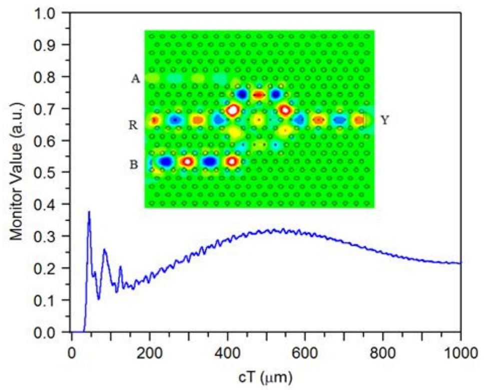


(b)

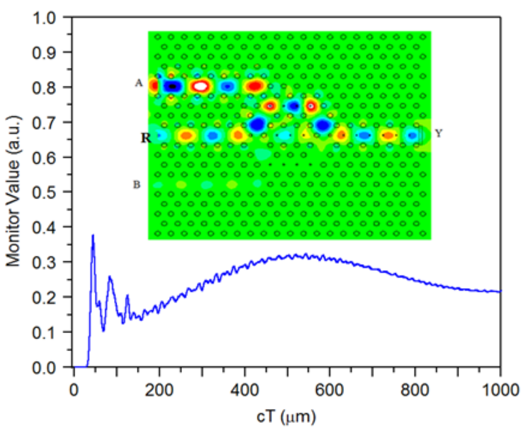
Fig. 6 (a) The schematic structure of three input AND gate and (b) 3D view of 3 input AND gate

Table 3 Truth table of three input AND gate

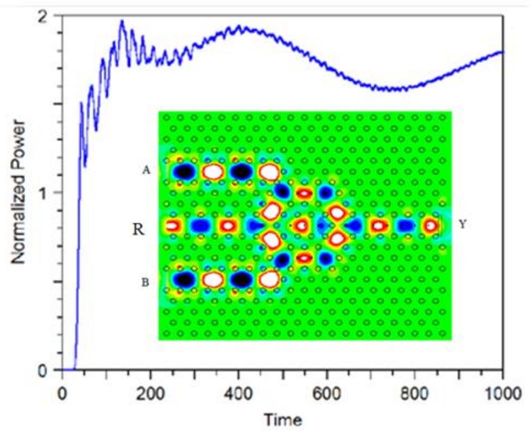
INPUT A	INPUT B	REF INPUT R	OUTPUT Y
0	0	1	0
0	1	1	0
1	0	1	0
1	1	1	1



(a)



(b)



(c)

Fig. 7 Signal propagation of three input AND gate (a) A=0,R=1,B=1and Y=0; (b) A=1, R=1,B=0 and Y=0 and (c) A=1,R=1,B=1 and Y=1

The electric field distribution of the three input AND gate is shown in Fig.7.

TABLE 4 FUNCTIONAL PARAMETER OF THREE INPUT AND GATE

INPUT A	INPUT B	REF INPUT	OUTPUT Y	RESPONSE TIME	CONTRAST RATIO	BIT RATE
0	0	1	0	7.256ps	42 dB	0.137 Tbps
0	1	1	0			
1	0	1	0			
1	1	1	1			

Table 4 shows the cumulative response of proposed AND gate. The functional parameters calculated such as contrast ratio, bit rate and response time.

4. Conclusion

An investigation of all optical two input and three input AND gate based on two dimensional photonic crystals is proposed and designed. The functional parameters calculated by using FDTD method. The contrast ratio, response period and bit rate of the proposed two input AND gate is 42 dB, 7.256 ps and 0.137 Tbps, and three input AND gate is 39.88 dB, 1.499 ps and 0.666 Tbps, respectively. By comparing all other reported logic gates, the proposed structure offers better contrast ratio with the footprint 12.2μm×10.6μm.Hence, the proposed optical logic gate is used for future high speed switching networks.

References

[1] Aryan Salmanpour, Ali Bahrami, Shahram

Mohammadnejad,“ Photonic crystal logic gates an overview”, Optical quantum electronics, Vol.47, No.7, pp.2249-2275, 2015.

[2] Ashkan, Pashamehr, Mahdi Zavvari, Hamed Alipour-Banaei, “All- optical AND/OR/NOT logic gates based on photonic crystal ring resonators”, Opto Electrons, Vol. 9, No. 4, pp.578-5843, 2015.

[3] Preeti Rani, Yogita kalra, RK. Sinha, “Design of all optical logic gates in photonic crystal waveguides”, Optik, Vol. 126, No. 9, pp.950-955, 2015.

[4] SK. Ajaykumar, S. Raghuwan, “Implementation of XOR/XNOR & AND logic gates by using Mach-Zehnder interferometers”, Optik, Vol.125, No.19, pp. 5764-5767, 2014.

[5] KE. Stubkjaer, “Semiconductor optical amplifier based all optical logic gates for high speed optical processing”, IEEE Journal on Selected Topics in quantum electronics, Vol.6, No.6,pp. 1428-1435, 2000.

[6] EH Shaik, Rangaswamy, “Multimode interference based photonic crystal logic gates with simple structure and improved contrast ratio”, Photonic network communication, Vol.34, No.1, pp.140-148, 2017.

[7] Weijia Liu, Daquan Yang, Guansheng Shen, Huiping Tian, Yuefeng Ji, “Design of ultra-compact all-optical XOR, XNOR,NAND and OR gates using photonic crystal multi-mode interference waveguides” , Optics& Laser Technology, Vol. 50, pp.55-64, 2012.

[8] M.Noori, N.Soroosh, “A comprehensive comparison of photonic band gap and self-collimation base 2D square array waveguides”, Optik, Vol.126, No.2, pp. 4775-4781, 2015.

[9] Aziz-Morad Vali-Nasab, Ali Mir, · Reza Talebzadeh, “Design and simulation of an all optical full adder based on photonic crystals”, Optical and Quantum Electronics, vol. 51, no. 5, pp. 1-14,2019.

[10] Guimin Lin, Xiyao Chen, DongxiaZhuang, “1 × 4 optical multiplexer based on the self-collimation effect of 2D photonic crystal”, Optik, vol. 125, no. 6,pp. 4322-4326, 2014.

[11] Taiyo Zhao, MehrnoushAsghari, Ferhad Mehdizadeh,“All optical digital 2-1 multiplexer using photonic crystal based non linear ring resonators”, Journal of electronic materials, vol. 48, no.4,pp.2482-2486,2019.

[12] Hamed Alipour Banaei, “Optical wavelength demultiplexer based on photonic crystal ring resonators”, Photonic networks communications, vol. 29, no.2, pp. 146-150, 2015.

[13] K.Venkatachalam, S.Robinson, SK. Dhamodharan, “Performance analysis of an eight channel demultiplexers using a 2D photonic crystal quasi square ring resonator”, Opto electron rev, Vol.25, No.2, pp. 74-79, 2017.

[14] Iman Ouahab Rafah, “A novel all optical 4x2 encoder switch based on photonic crystal ring resonators”, Optik, vol.127, no.19, pp.7835-7841, 2016.

[15] Somaye Serajmohammadi, Hamed Alipour-Banaei, and Frhadmehdizadeh, “All optical decoder switch based photonic crystal ring resonator”, Optical and Quantum Electronics, vol. 46, no. 6, pp. 1109-1115,2015.

[16] T.Betsy Saral, S.Robinson, R. Arunkumar, “Two dimensional photonic crystal based compact power splitters’’, International journal of Photonics and Optical Technology,Vol.2,No.4,pp. 1-5, 2016.

[17] R.Arunkumar, T.Suganya, S.Robinson, “Design and analysis of photonic crystal elliptical ring resonator based pressure sensors”, Photonic Optical technology, Vol.3, pp.30-33, No.1, 2017.

[18] KV.Shanthi, S.Robinson, “Two dimensional photonic crystal based sensor for pressure sensing”, Photonic sensors, Vol.4, No.3, pp. 248-253, 2014.

[19] R.Rajasekar, K.Parameshwari, S.Robinson, “Nano optical switch based on Photonic crystal based ring resonator”, Plasmonics, Vol.14, No.6, pp.1687-1697, 2019.

[20] S. Robinson and R.Nakkeeran, “Couple mode theory analysis for circular photonic crystal ring resonant or based add drop filter”, Optical engineering, Vol.51, No.11, pp. 114001, 2012.

[21] S. Robinson and R.Nakkeeran, “PCRR based band pass filter for C and L+U bands of ITU-T G.694.2 CWDM systems”, Optics and Photonic Journal, Vol. 1, No. 3, pp. 142-149, 2011.

[22] Enaul haq Shaik and Nakkeeran Rangaswamy, “Design of Photonic crystal based all optical AND gate using T shaped waveguide”, Journal of Modern Optics, Vol. 63, No. 10, pp.941-949, 2015.

[23] Yuhei Ishizaka, Yuki Kawaguchi, Kunimasa Saitoh, Masanori Koshiba, “Design of ultra-compact all optical XOR &AND logic gates with low power consumption”, Optics communications, Vol. 284, No. 14, pp. 3528-3533, 2015.

[24] Parisa Andalib, Nosrat Granpayeh, “All-optical ultra compact photonic crystal AND gate based on nonlinear ring resonators”, Journal of the Optical Society of America, vol.26. no.1, pp.10-16, 2009

[25] Mohammad Danaie , Hassan Kaatuzian, “Design and simulation of an all-optical photonic crystal AND gate using nonlinear Kerr effect, Optical and Quantum

Electronics, Vol. 44,pp. 27-34, 2012.

[26] Yi-Pin Yang ,Kuen-Cherng Lin , I-Chen Yang ,Kun-Yi Lee ,Yen-Juei Lin ,Wei-Yu Lee Yao-Tsung Tsai, “All-optical photonic crystal AND gate with multiple operating wavelengths”, Optics Communication, Vol. 297, pp. 165-168, 2013.

[27] Majid Ghadrdan, Mohammad Ali Mansouri-Birjandi, “Concurrent implementation of all-optical half-adder and AND & XOR logic gates based on nonlinear photonic crystal”, Optical and Quantum Electronics , vol. 45,no.10,pp.1027-1036,2013.

[28] Tamer S. Mostafa, Nazmi A. Mohammed & El- Sayed M. El-Rabaie, “Ultra-High bit rate all-optical AND/OR logic gates based on photonic crystal with multi-wavelength simultaneous operation”, Journal of modern optics, Vol. 66, No. 9, pp.1005-1016, 2019.