

Novel All Optic Logic Gates using 2D Photonic Crystal Structure

Achary SN*

Faculty of Physics Ganjam College, Ganjam, India

Abstract

A novel scheme for implementation of all-optical logic gate based on 2D photonic crystal structure has been proposed. The design and simulation of novel all-optical logic gates based on two dimensional photonic crystals are reported in this paper. The proposed PCS is comprised of two-dimensional lattice of air holes in a square Silicon substrate having refractive index of 3.15. The operational wavelength of the input ports is 1.55 μm . Since the structure is a simple geometric in its dimension with clear operating principle, it is potentially applicable for photonic integrated circuits. The logic operations are realized by a control signal and the input signal (s) applied across two adjacent faces, while the output is obtained along one of the remaining face. No control signal is used for AND Gate, However to realize OR, NOT and NOR Gates a control signal is applied at the third face. With same structure one can realize all optic logic gates. The steady state field distributions at different input sates are obtained by FDTD simulation. The results indicate the potential candidature of the photonic crystal for optical digital integrated circuits.

Keywords: Optical logic gates; Photonic crystal structure; Finite Difference Time Domain; Kerr nonlinearity

Introduction

Photonic crystals (PC) are dielectric material in which the refractive index is periodically varied in space. In PC for some frequency ranges the light waves are not propagating through the structure, such frequency range is called forbidden gap of photons. The doping of impurity or creating defects produce strong localization of a resonant photon. This phenomenon will allow a perfect control of light propagation and radiation. Introducing line defects in PC results in a photonic crystal waveguide. All optic logic gates are key elements in different signal processing techniques. It is based on Mach-Zehnder Interferometer (MZI) [1], semiconductor optical amplifier (SOA) [2], SOA based on ultrafast nonlinear interferometer [3], SOA with optical filter [4] and semiconductor laser amplifier loop mirror [5]. But all these schemes suffered due to high power consumption, speed, narrow operating wavelength range and signal to noise ratio. Photonic crystal structures (PCS) have been attractive element for this purpose because of its dimension, low loss structure and high operating speed [6]. Thus photonic crystal based all optic logic gates are considered as key components in future photonic integrated circuits and hence such optical devices have attracted significant research in recent years. Most of the recent reported works are based on nonlinear optics, but these devices again suffer due to high power consumption and narrow operating frequency range. Further there are very few references available, where optical logic gates are based on photonic crystal structure. For example in reference [7], OR and XOR logic gates are realized by introducing a line defect along TX-direction, while in reference [8], XOR gate is realized by a line defect asymmetric Y branch waveguide [9]. The different PCS, reported in the literature have mainly two disadvantages. Complex geometry of the structure which is very difficult to fabricate even using the most advanced techniques and secondly the materials where maximum work on logic gates based on PCS have been reported is silicon dioxide (Glass). However, the corrosion effect may take in to account in fabrication process. The effect of electro-pulsing treatment (EPT) on the microstructure, mechanical properties and corrosion found that the elongation to failure of materials obtains a noticeable enhancement with increased EPT processing time while slightly sacrificing strength. The Grain coarsening and decreased ductility were brought in with longer EPT duration time. Fracture surface analysis shows that transition from

intergranular brittle fracture to transgranular dimple fracture takes place with an increase in processing time of EPT. Meanwhile, corrosion behavior of silicon is greatly improved with increased EPT processing time and the surface observation with the beneficial effect of forming a protective film [10]. Unfortunately this material is not suitable for drilling fine holes or structures required as per the simulation. For example an attempt to catch circular air holes in silicon oxide substrate using FIB technique forms cracks along the circumference. While this issue can be taken if silicon oxide substrate will be replaced by silicon substrate. We in this investigation, proposed a simple structure on a silicon substrate which is easier for fabrication. Using FDTD simulation it is shown that one can realize AND, OR, NOT, NOR and all Optic Logic Gates in this structure.

FDTD Method

Several computational methods have been employed for analysis of photonic crystal structure, including plane wave expansion (PWE) method, transfer matrix method, Green's function method and finite difference time domain method. But we have employed the FDTD method based on Yee's algorithm, to study the 2D-PCS, because the computational time and memory requirements are reduced [11,12]. The propagation of electromagnetic waves through photonic crystal structure is governed by Maxwell's four equations in a linear medium with the sources and are

$$\begin{aligned}\nabla \times \vec{E} &= -\mu \frac{\partial \vec{H}}{\partial t} \\ \nabla \times \vec{H} &= \epsilon \frac{\partial \vec{E}}{\partial t} \\ \nabla \cdot \vec{E} &= \nabla \cdot \vec{H} = 0\end{aligned}\quad (1)$$

Using these equations, magnetic field components can be expressed

*Corresponding author: Achary SN, Faculty of Physics Ganjam College, Ganjam, India, Tel: 2543289; E-mail: acharysurya1@gmail.com

Received June 02, 2015; Accepted June 23, 2015; Published July 03, 2015

Citation: Achary SN (2015) Novel All Optic Logic Gates using 2D Photonic Crystal Structure. J Material Sci Eng 4: 178. doi:10.4172/2169-0022.1000178

Copyright: © 2015 Achary SN. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

in form of Helmholtz equation, which is given by

$$\frac{\partial}{\partial x} \frac{1}{\epsilon(x)} \frac{\partial}{\partial x} H(x) + \frac{\omega^2}{c^2} H(x) = 0 \tag{2}$$

Equations (1) and (2) are discretised so that the E and H fields are solved from the E and H field at a precise time step. The 2-D TE mode FDTD used in this paper is

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu} \left[-\frac{\partial E_z}{\partial y} \right]$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu} \left[\frac{\partial E_z}{\partial x} \right]$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\epsilon} \left[\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \right] \tag{3}$$

Each field component is updated from the data at the previous time step. The Gaussian beam is initiated in the grid, travels through, reflects from, refracts in and resonates inside the photonic crystal. Where $\epsilon(r)$, $\mu(r)$, $\sigma(r)$ are permittivity, permeability and conductivity of the material and all are in the function of position. For our simulation, we have used PML boundary condition. Further time step is so chosen that stability criteria is satisfied and the output power normalization can be calculated as follows,

Power Normalization

The Complex pointing vector is given by,

$$\vec{P} = \vec{E}(\omega) \times \vec{H}^*(\omega) \tag{4}$$

It is used to calculate the power flow in a particular direction and the time-averaged power flowing across a surface is given by

$$power(\omega) = \frac{1}{2} \int_{s} \text{real}(\vec{P}) \cdot d\vec{s} \tag{5}$$

Note that the propagating power is proportional to the real part of the Poynting vector only, which is related to the conservation of energy for the time-averaged quantities. The factor of 1/2 is related to the time averaging of the TW fields. The imaginary part of the Poynting vector relates to the non-propagating reactive or stored energy, such as one might find in the evanescent tail of light being reflected by total internal reflection (TIR) [13,14].

Structure

The proposed 2D PCS is based on 15 × 15 air holes with lattice constant $a_x=0.575 \mu\text{m}$ and $a_y=0.575 \mu\text{m}$. The silicon substrate having dielectric constant 11.5 is drilled with air holes of radius $r=0.115 \mu\text{m}$. The input signals are applied along face 1 and face 2, whereas the control signal is used along face 3. The output is obtained along face 4 as shown in the Figure 1. In the following paragraphs the various configurations of logic gates are presented.

Realization of Logic Gates

To realize AND gate input signals are initiated in face-1 and face-2, while output is calculated at face-4. Some of the simulation results are shown in Figure 2a is observed in Figure 2b for inputs given to face 1, and face 2, a strong signal is obtained at the center of face-4. While one signal is taken out either from face-1 and face-2, no signal reaches the center of face-4. The simulation results are presented in Table 1.

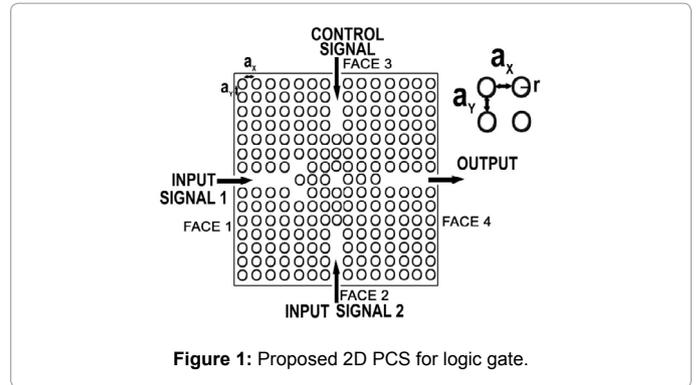


Figure 1: Proposed 2D PCS for logic gate.

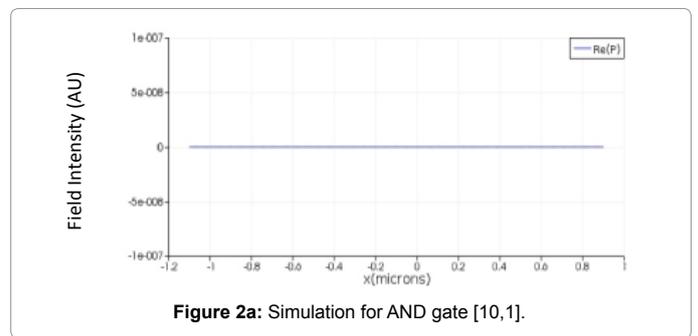


Figure 2a: Simulation for AND gate [10,1].

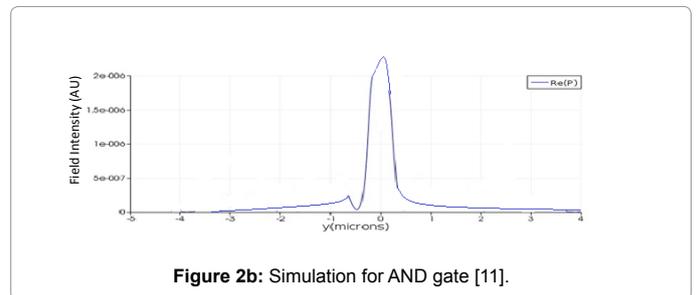


Figure 2b: Simulation for AND gate [11].

Input 1	Input 2	Out Put
1	1	1
1	0	0
0	1	0
0	0	0

Table 1: Logic AND gate.

Input 1	Input 2	Control Signal 3	Out Put
1	1	1	1
1	0	1	1
0	1	1	1
0	0	0	0

Table 2: Logic OR gate.

We further investigate the performance of OR gate using the cross waveguide structure using a control signal. OR gate encompasses of two inputs and an output. The stimulated results for [11],[10],[01] are shown in Figures 3a-3c and the corresponding logic gate is presented in Table 2, where the output is logically '1' if and only if both of the input values are '0'.

A NOT Gate is realized with the control signal. The simulation results in the output are shown in Figure 4 and the results are shown

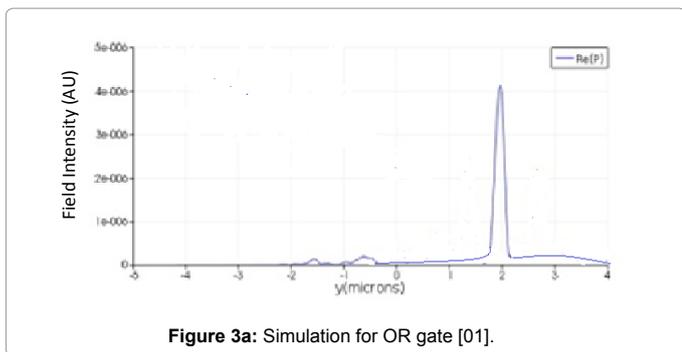


Figure 3a: Simulation for OR gate [01].

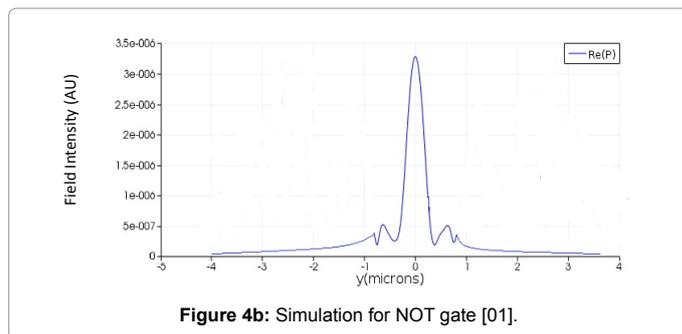


Figure 4b: Simulation for NOT gate [01].

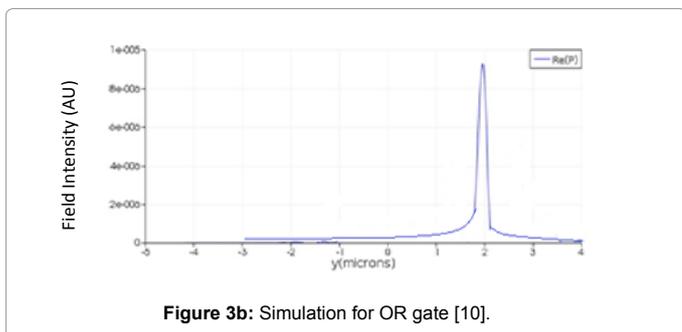


Figure 3b: Simulation for OR gate [10].

Input 1	Input 2	Control Signal 3	Output
1	1	1	1
1	1	0	1
1	0	1	1
1	0	0	0

Table 4: Logic NOR Gate.

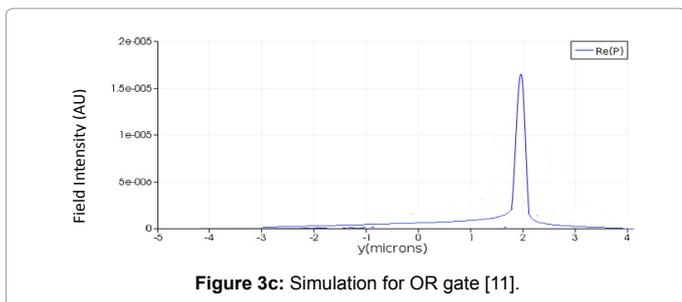


Figure 3c: Simulation for OR gate [11].

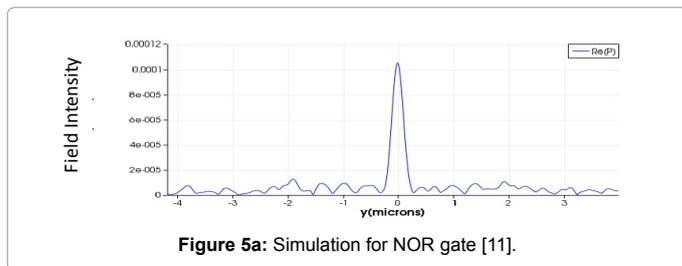


Figure 5a: Simulation for NOR gate [11].

Input Signal 2	Control Signal	Out Put
0	1	1
1	1	0

Table 3: Logic NOT gate.

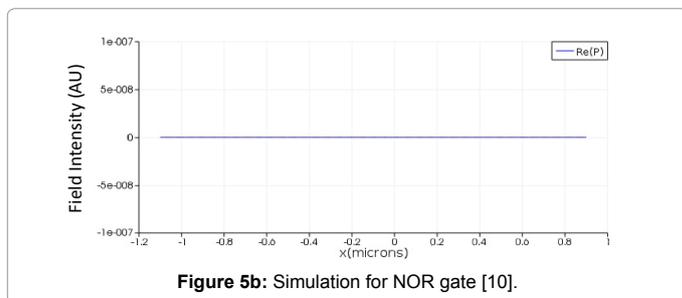


Figure 5b: Simulation for NOR gate [10].

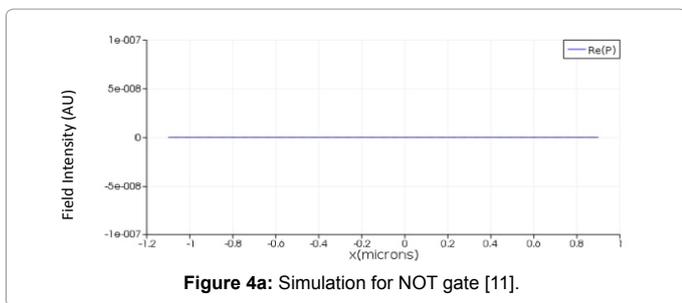


Figure 4a: Simulation for NOT gate [11].

in Table 3. Similarly In this case of NOR gate we apply a fixed signal into the input 1, by applying input signal 2 and control signal 3, we find NOR Gate. The Simulated results are shown in Figures 4a and 4b and corresponding results are presented in Table 4. We use the signals 2 and the control signal 3 and the output taken along face 4 in Figures 5a and 5b.

Conclusion

A design procedure for AND, OR, NOT, and NOR Optical operation in a 2D PCS on silicon substrate is proposed in this paper. 2D PCS is realized by drilling air holes so as to form line defect. To the best of our knowledge this is the first report on optical logic gate in silicon substrate. The proposed device benefits a simple and small structure. The structures can be strong candidates for future photonic integrated circuits. While the performance of such logic gates is still severely limited, similar to most of the optical logic gates proposed so far, by the characteristic times of the relevant optical nonlinearity, the use of the proposed mechanism of transmission control in PBG structures allows the switching power density to be appreciably reduced. An important advantage of the proposed class of optical logic gates is also associated with the possibility of performing different logic operations with the same structure by changing the power densities of logic Gates.

References

1. Zhao D, Zhang J, Yao P, Jiang X, Chen X (2007) Photonic crystal Mach-

- Zehnder interferometer based on selfcollimation. Applied Physics Lett 90: 231114-231120.
2. Soto H, Diaz CA, Topomondzo J, Erasme D, Schares L, et al. (2002) All-Optical AND gate implementation using cross polarization modulation in a semiconductor optical amplifier. IEEE Photon Technol Lett 14: 498-500.
 3. Miyoshi Y, Ikeda K, Tobioka H, Inoue T, Namiki S, et al. (2008) Ultrafast all-optical logic gate using a nonlinear optical loop mirror based multi-periodic transfer function. Opt Express 16: 2570-2577.
 4. Houbavlis T, Zoiros K, Hatziefremidis A, Avramopoulos H, Occhi L, et al. (1999) 10 Gbit/s alloptical Boolean XOR with SOA fiber Sagnac gate. Electron Lett 35: 1650-1652.
 5. OR Gate. Hyperphysics.phy-astr.gsu.edu.
 6. Avramopoulos H (2001) Optical TDM devices and their applications, in Optical Fiber Communication (OFC 2001). Optical Society of America, Washington, DC.
 7. Kabilan AP, Susan Christina X, Elizabeth Caroline P (2009) Realization Of Optical Logic Gates Using Photonic Crystal. ICOP 2009- International Conference on Optics and Photonics Chandigarh, India.
 8. Lee KY, Lin JM, Yang YC, Yang YB, Wu JS, et al. (2008) The Designs of XOR Logic Gates based on Photonic Crystals. Proc SPIE.
 9. Kabilan AP, Susan Christina X, Elizabeth Caroline P (2010) Photonic Crystal based all Optical OR and XOR Logic Gates. Second International conference on Computing, Communication and Networking Technologies, IEEE 2010.
 10. Xiaoxin Y, Lingsheng W, Tse Zion TH, Guoyi T, Guolin S (2015) Effects of high-energy electro-pulsing treatment on microstructure, mechanical properties and corrosion behavior of Ti-6Al-4V alloy. Materials Science and Engineering: C 49: 851-860.
 11. Yee KS (1966) Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media. IEEE Trans Antennas Propag 14: 302-307.
 12. Qui M, He S(2000) Numerical method for computing defect modes in two-dimensional photonic crystals with dielectric or metallic inclusions. Phys Rev B 61: 12871-12876.
 13. Qui M, He S (2001) FDTD algorithm for computing the off-plane band structure in a two-dimensional photonic crystal with dielectric or metallic inclusions. Phys Lett A 278: 348-354.
 14. Tripathy SK, Subikash S, Mahspstro C, Dash SP (2012) Implementation of photoniccrystal structure. Opticcommunication 286: 3234-3237.