A

DISSERTATION REPORT

ON

Designing and Analysis of all optical XOR, NOT, OR and AND Logic Gates Based On 2D Photonic Crystals T-shaped Waveguide

submitted in partial fulfillment for the award of degree of

MASTER OF TECHNOLOGY IN ELECTRONICS AND COMMUNICATION ENGINEERING

Submitted by:

Nilesh Kumar Yadav

(2017PEC5086)

Supervisor:

Mr. Sanjeev Agrawal

Associate Professor, ECE Department

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
MALAVIYA NATIONAL INSTITUE OF TECHNOLOGY
JAIPUR (JUNE 2019)

CERTIFICATE

This is to certify that the dissertation report entitled "**Designing and Analysis of all optical XOR, NOT, OR and AND Logic Gates Based On 2D Photonic Crystals T-shaped Waveguide**" in partial fulfillment of the requirement for the award of degree of **Master of Technology** in **Electronics and Communication Engineering** during the academic year **2018-2019** has been successfully completed and presented by **Nilesh Kumar Yadav** to the best of my knowledge. The work has been found satisfactorily carried out under my supervision, and is approved for submission.

Date:
Place:

Mr. Sanjeev Agrawal
Associate Professor
Dept. of ECE, MNIT JAIPUR
INDIA 302017

Declaration

I, Nilesh Kumar Yadav, declare that this Dissertation titled as **"Designing and Analysis of all optical XOR, NOT, OR and AND Logic Gates Based On 2D Photonic Crystals T-shaped Waveguide**" and the work presented in it is my own and that, to the best of my knowledge and belief.

I confirm that major portion of the report except the refereed works, contains no material previously published nor present a material which to be substantial extent has been accepted or the award of any other degree by university or other institute of higher learning. Wherever I used data (Theories, results) from other sources, credit has been made to that source by citing them (to the best of my knowledge). Due care has been taken in writing this thesis, errors and omissions are regretted.

Date: Nilesh Kumar Yadav

Place: (2017PEC5086)

ACKNOWLEDGEMENT

To discover, analyze and to present something new is to venture on an untrodden path towards and unexplored destination is an arduous adventure unless one gets a true torch bearer to show the way. I would have never succeeded in completing my task without the cooperation, encouragement and help provided to me by various people. Words are often too less to reveals one's deep regards. I take this opportunity to express my profound sense of gratitude and respect to all those who helped me through the duration of this thesis. I acknowledge with gratitude and humility my indebtedness to **Mr. Sanjeev Agrawal**, **Associate Professor, Department of Electronics and Communication Engineering Malaviya National Institute of Technology, Jaipur,** under whose guidance I had the privilege to complete this thesis. I wish to express my deep gratitude towards him for providing individual guidance and support throughout the dissertation work.

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Nilesh Kumar Yadav
(2017PEC5086)

Abstract

To overcome all the disadvantages of SOAs based optical logic gates an alternative material photonic crystal is used in fabrication of logic gates. Photonic crystals are that material which has properties of varying refractive index periodically. Due to its nonlinearity property, the photonic crystal widely used in all optical logic gates. Many researchers move towards PhCs material because of its unique properties. All optical logic gates have low power consumption and compact in size and can be widely used in optical communications for number of application.

The objective of this thesis is proposal of a simple T-shaped waveguide structure based on 2D photonic crystal (PhCs) in square lattice or cubic lattice as XOR, NOT, and OR logic gates, and also as an AND gate with modification in the radius of its directional rods at its junction. Its operation depends upon the phase difference of the input light signals launched at input ports. The proposed structure has two input ports A & B and one output port Y. The phase of the light launched to port *A* of the waveguide is zero and phase of light signal varies for port B. For the NOT logic gate, port *B* is used as the reference input with 180° phase. The phase of the input light signal launched to port *B* is 0^0 for OR and AND while in case of XOR, it is 180° phase. Simulation is done with the help of plane wave expansion (PWE) and Finite Difference Time Domain (FDTD) method at a wavelength of 1550 nm for all optical logic gates discuss in this thesis. We determined the ON to OFF contrast ratio (CR) of XOR, OR and NOT logic gate is 55.38 dB while it is 6.033 dB for AND gate, with a fast response time of less than 0.1 ps. Finally, we can be concluded that, the proposed structure can be used as a common structure for XOR, OR and NOT logic gate with having fast output response to be utilized as a basic component in the future Photonic ICs.

Contents

List of Acronyms

1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
AOLG	All Optical Logic Gates
EM	Electromagnetic Waves
FDTD	Finite Difference Time Domain
KHz	Kilohertz
MMI	Multi-Mode Interference
PBG	Photonic Band Gap
PCFs	Photonic Crystal Fibers
PCRR	Photonic Crystal Ring Resonators
PhCs	Photonic Crystal
PIC	Photonic Integrated Circuits
PWE	Plane Wave Expansion
Si	Silicon
SOAs	Semiconductor Optical Amplifiers
TE	Transverse Electric
THz	Terahertz
TIR	Total Internal Reflection
TM	Transverse Magnetic

List of Figures

Figure **Page**

List of Tables

CHAPTER 1

Introduction to Photonic Crystal

In our daily life, the semiconductor has played an important role that changed the world beyond anything. But semiconductor based devices have many disadvantages. Main disadvantage is its operating speed and synchronization problem. Semiconductor based devices have low speed and high power consumption. In this technology chip density is also low [1] Photonic crystal a new type of material proved advantageous over all disadvantages in conventional designing. Some of its advantages are Light of particular wavelength range reflected by Photonic crystals which results in one mode of cavities unlike the metal cavities. All wavelengths reflected by the metal which results in infinite mode. Photonic crystals can withstand with high electric fields. The size of photonic crystal devices are in order of wavelength of light. Hence the devices are compact in size. Processes the data at high speed as the travelling speed in structure is speed of light. These devices protected to short circuits as well as noise as the information carriers are photons unlike electrons in metallic wires. Photonic crystal based devices have low power consumption. Photonic crystals confine the light highly in the structure due to large difference present for effective index. PhC Controls the spontaneous emission in the lattice.

Photonics technology based devices advantageous over the semiconductor technology based devices as-

(i) Light in dielectric medium can travel faster than the electrons in medium of metal. It leads to faster rate data transmission. High speed of computing system achieved.
(ii) Lights are less interacting than electrons in medium. It leads lesser energy loss in the travelling path.
(iii) High density integration on chip.

Worldwide so many research works have been done to realize compact size all optical computing systems with less power consumption and have faster processing. The main idea behind the design of PhCs is to control the flow of photon. The traditional mechanism used for manipulation of flow of photon is TIR but the photonic crystals provide totally different mechanism for control of light (the PBG control the flow of light).

1.1 Historical Perspective of Photonic Crystals

In 1987, after invention of new category material i.e. PhCs, semiconductor technology based logic devices disappear after the idea proposed by Yablonovitch [2] and John [3]. Yablonovitch stated that with in periodic dielectric medium, states density can modify to control the spontaneous emission of electron in semiconductor materials and on other hand John made an effort to use these dielectric medium to control of photons.

In PhCs structures propagation of light wave is not allowed in a particular directions for specific frequencies range. These specific frequency ranges are called as Photonic Band-gap (PBG) similar to band gap in semiconductor. Due to their unique properties this PhCs structure are very useful in telecommunication because of their high speed and low power consumption [1, 4]. PhCs technology based components have compact size and can operate at low power. In 1991, Yablonovitch presented the first 3D band gap in the microwave era. In 1996, Thomas Krauss explained the 2D PhC at optical wavelength [5]. In 1998, Philip Russell developed first commercial used photonic crystal fiber [6]. Based on PhCs technology has been proposed all optical logical operations, combinational circuit and sequential circuit etc [7-9].
Table 1.1 shows Historical progress of PhCs.

1987	1D Photonic Crystal which show stop band
1987	2D Photonic Crystal proposed by Yablonovitch and John
1991	Yablonovitch explained 3D PhC in micrometer range
1996	Thomas Krauss explained the 2D PhC at optical wavelength
1998	First commercial used photonic crystal fiber was developed by Philip Russell

Table 1.1 Historical progress of PhCs.

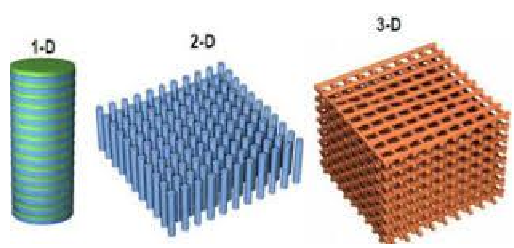
1.2 Photonic Crystal

A new category of material, Photonic crystal is an optical material in which dielectric constant changes periodically. Crystal lattice is the space in which dielectric constant placed in particular pattern and distance between two dielectric crystals is lattice constant. Refraction and reflection occurs at each interface of the dielectric material when the light propagates inside the crystal. It causes interference due to which some wavelengths close to periodicity of dielectric constant do not propagate through the photonic crystal. These forbidden wavelengths form the band gap which is similar to electronic band gap [1]. The study of photonic crystals is similar to the semiconductor in solid state physics. This PBG controls the flow of photon or light. This enables to change the flow of photons by engineering the crystals for particular application.
There are many differences between photonic crystal and lattice of ions (crystals). In photonic crystal, the particles which scattered are photon whereas in semiconductor electrons scattered through the lattice. The PhCs based on Maxwell’s equation while the other based on Schrodinger’s equation. Semiconductor crystal forbidden the certain energy while photonic crystal forbidden certain range of frequency. This forbidden range of frequency does not allow light to propagate through the lattice. The photonic crystals are artificially fabricated material for particular PBG in contrast to the naturally occurring semiconductor material. The main problem during fabrication is the size of lattice constant must be around half the wavelength of Electromagnetic waves.

The properties of PhCs can be changed through the doping in which dielectric rods are added or removed in the certain region. The process of addition or removal of dielectric material is known as defect (Point defect or Line defect). This defect causes localization of electromagnetic waves (EMW) in the PBG [3]. Periodicity of photonic crystal is broken by introducing these defect which leads to the number of applications.

1.3 Types of Photonic Crystal

On basis of geometry, Photonic crystal can be divided into three categories: One-Dimensional (1D), Two-Dimensional (2D) and Three-Dimensional (3D) PhCs [10, 11].
In 1D PhC structure, dielectric material changes only in one direction and the photonic band gap exists only in that direction. The propagation of EM wave is affected along that lattice direction where refractive index is changed. This is simple as well as easier to fabricate the structure. This is used as mirror in vertical cavity surface emitting lasers (VCSELs) from the time when PhC are not known [12]. It also known as distributed Bragg mirror. The different types of photonic crystals are shown in below Fig. 1.1



(a) **(b)** **(c)**

Fig1.1 Schematic representation of PhCs (a) one-dimensional (b) two-dimensional (c) three-dimensional [13]

In 2D PhC, the refractive index is periodically changed along two directions and uniform in third direction. It is formed by placing periodically dielectric rods in the air or with air rods in the dielectric substrate. The PBG are exist in the plane of periodicity and light do not propagate in this plane [5]. For propagation of light in this plane, the harmonic modes divided into two independent polarizations i.e. TE and TM mode. Each polarization has its own different band structures. It is also possible that the PBG may exist for one of polarization but not for other one. By creating the defects, light can be localized in the band gap and crystals' face can support the surface states. In 3D PhC, the refractive index is changed periodically in all the direction. That is the reason that there is no axis along which light can propagate in the structure [14].

It results in complete band gap. It is very difficult to localize the EM waves at the point defects and propagate through the linear defect. In 1D and 2D, light can localize at the point or line defect but in 3D there is extra capability to localize the light in all directions. The two-dimensional PhCs have attracted the researchers and scientists because of its easy fabrication and analysis. In this dissertation, 2D PhCs with square lattice are considered.

1.4 Localization of Light in 2D Photonic Crystals

1.4.1 Point Defect in Photonic Crystals

There are various types of localization in photonic crystal. Basically localization is a medium or path to travel light in photonic crystal. To allow light to travel in photonic crystal there must to break the periodicity of the structure. Point defect can be created in the structure by increasing or decreasing the radius of single rod and also by removing the single rod or created hole in the structure. After breaking the periodicity, a single localized mode created. These localized modes decays exponentially. Field profile or photonic band gap can be obtained by plane wave expansion (PWE) method. With the help of Bloch boundary condition we defined field profile for localized defect modes. Photonic band gap gives the range of frequency which does not allow light to travel in photonic crystal.
Below figure shows the cross-section view of 2D-PhC having point defect.

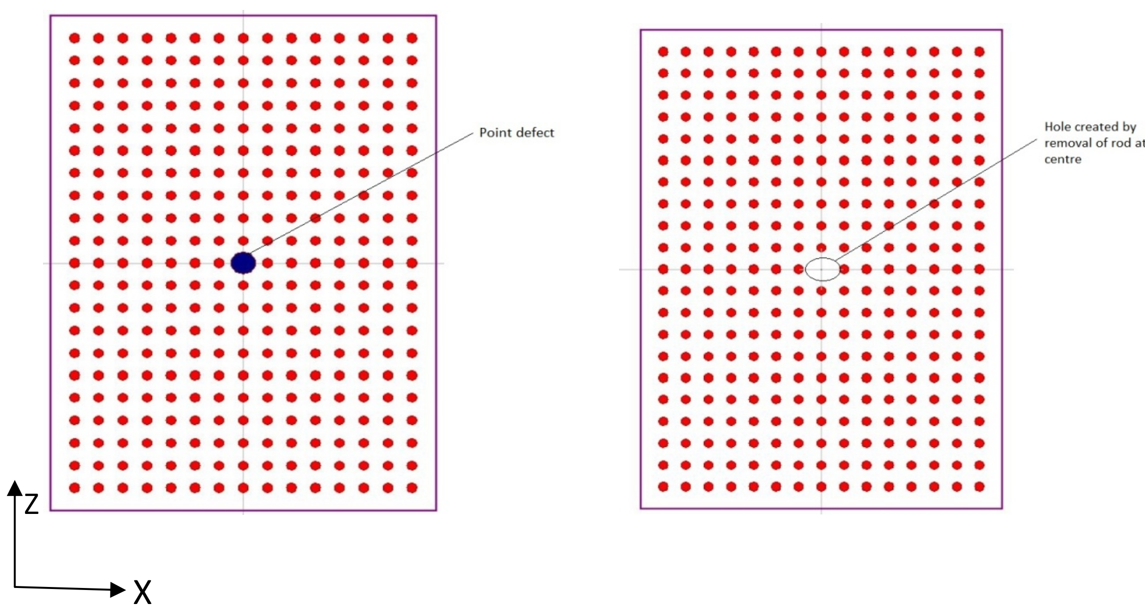


Fig 1.2 Point defect in PhCs with cross-sectional view**.**

1.4.2 Line Defect in Photonic Crystals

To allow light to travel in photonic crystal there must to break the periodicity of the structure. Basically localization is a medium or path to travel light in photonic crystal. We can see that a point defect inside a regular PhCs structure not allows light waves to travel for the range of frequencies which fall into the PBG. This idea could be further used to produce a waveguide for light signals by sequentially creating point defects by increasing rods or holes of a single layer (either row or column). This type of defects used to guide the light from one position to another [15]. The main idea behind this is to form a waveguide from the photonic crystal by changing a linear series of crystal as shown in Fig. 1.3. Light within the frequency range in the photonic band gap that propagates in the waveguide is confined to the defect and can be directed along the defect [16]. The linear defect structure still has one direction in which discrete translational symmetry is conserved within the plane. Mechanism of guiding light is index guiding i.e. TIR in the conventional dielectric waveguides but this mechanism confine the line only in the region of higher refractive index. In this the mechanism of guidance is photonic band gap which is independent of the material's properties that filled in the core. This is important property for the number of applications in which reduction of interaction between the dielectric material and light is required.

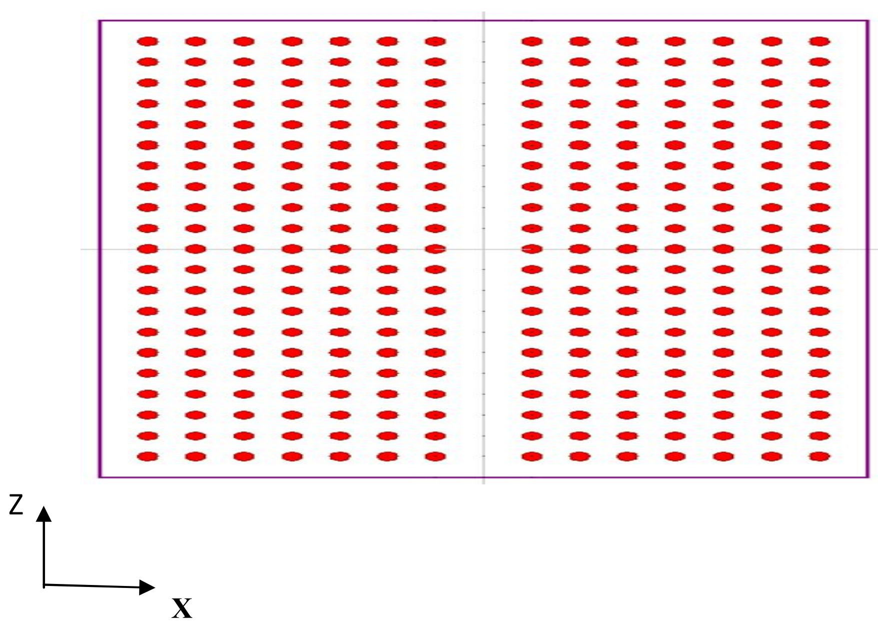


Fig. 1.3 Line defects in PhCs with cross-sectional view**.**

1.5 Advantages of Photonic Crystals

Photonic crystals are very advantageous over the conventional optical devices. It has main advantage is to control optical properties and confinement of light by engineering the design of structure.
Some of its advantages are listed below:

1. Light of particular wavelength range reflected by Photonic crystals which results in one mode of cavities unlike the metal cavities. All wavelengths reflected by the metal which results in infinite mode.

2. Photonic crystals can withstand with high electric fields.

3. The size of photonic crystal devices are in order of wavelength of light. Hence the devices are compact in size.

4. Processes the data at high speed as the travelling speed in structure is speed of light.

5. These devices protected to short circuits as well as noise as the information carriers are photons unlike electrons in metallic wires.

6. Low power consumption due to linear property of photonic crystal.

7. Photonic crystals confine the light highly in the structure due to large difference present for effective index.

8. Controls the spontaneous emission in the lattice.

1.6 Disadvantages of Photonic Crystals

Photonic crystal offers few disadvantages also. Its complexity to design on the 3D scale is main disadvantage [6]. Many experiment occurred to yield efficient results. Its designing cost is also high. Photonic crystals are more expensive than the conventional devices.
Due to its various advantages, photonic crystal based devices are developed rapidly to meet the growing demand of high speed and capacity.

1.7 Problem Formulation

All research work done for designing optical logic gates based on semiconductor optical amplifiers (SOAs) have many disadvantages which are listed as below;

I. SOAs based logic gates have low contrast ratio which must be improved.
II. There are various reflections losses in SOAs based optical logic gates and must be reduced for cascading of two optical gates efficiently.
III. For compact size of logic gates the fabrication error tolerance should be improved.

1.8 Objective of Thesis

I. To improve contrast ratio (CR) with optimized output power for logic '1' and logic '0' at output port.
II. To design all optical logic gates such as XOR, NOT, OR and AND based on 2D photonic crystals with high output response.
III. Calculation of response time with the help time evolving curve.

1.9 Organization of Thesis

Chapter 2 includes literature survey regarding topic of designing all optical logic gates with 2D photonic crystals. In beginning of thesis we need to study various research papers published in recent years related to our topic.

Chapter 3 contains the numerical analysis to analyze the performance characteristics of proposed structure. Basically this chapter describes the Maxwell's equation for EM waves and simulation method for operation of logic gates.

Chapter 4 presents designing of all optical logic gates based on 2D photonic crystal and its simulation results. In this chapter we obtained the contrast ratio and calculate the output time response.

Chapter 5 includes the modified structure for optical AND gate and its results.

Chapter 6 contains conclusions of thesis and future work.

CHAPTER 2

Literature Survey

In recent years, Optical logic gate based on photonic crystal has gained much interest because of its unique properties. Many researchers started to pay more attention to design optical logic gates based on photonic crystal. Photonic crystals are one of important optical media for light propagation and to form optical processors, data handler and optical communication system. In general optical logic gates based on their designing and fabrication are divided into three categories such as resonators, interference waveguide, and self- collimation. Some researchers designed the logic gate based on the resonators. The resonators can be linear or nonlinear. Optical logic gates based on the interference waveguides also studied by many researches because of its easy modeling and easy to understand its principle. Self collimation phenomenon for the designing of logic gate is also studied by many authors.
The literature survey of all optical logic gate based on Photonic Crystals by various publishers in previous years is as follow:

Chunrong Tang, Xinyu Dou, H.Yin , Bin Wu, Q Zhao **[17]**

This paper gives knowledge about designing various all optical logical gates on a 2D Photonic crystal. The authors proposed a model to design of logic gate based on multimode interference (MMI). In this model a phase shift is introduced between the inputs ports with having different length of waveguide, this phase shift make suitable logic gates to be directly used for logic operations of binary- phase- shift- keying (BPSK). In this paper various logic gates such as XNOR, XOR, NAND and OR are realized. These gates are simulated with the help of finite difference and time domain (FDTD) and plane wave expansion (PWE) method. The authors numerically calculated the contrast ratio of 21 dB for XOR, 17 dB for XNOR and 21 dB for NAND and OR in C-Band (1530-1565 nm). Power consumption is low and size of component is small because of linearity properties of material. Therefore this design of the optical logic gate has the potential to constitute PICs that will be utilized in, all-optical networks, all-optical signal processing and photonic computing.

JunjieBao, J.Xiao, LinFan, XiaoxuLi, Yunfei Hai, TongZhang, C.Yang **[18]**

The authors in this paper investigated a new configuration for the designing of all optical logic gates based on photonic crystals (PhCs) in 2D square lattice of Si rods in silica (SiO_2). The proposed structure has two components, one is two photonic crystal ring resonators (PCRRs) and another one is cross shaped waveguide.

This structure is design without using any semiconductor optical amplifiers (SOAs) and non linear materials. The performance of this optical logic gates are analyzed by PWE and FDTD method. The numerically demonstration of structure shows that these structure acts as logic NOR and NAND gate. The authors observed the results and concluded that the proposed structure can be used as universal NOR and NAND logic gate. It can be used in ICs due to its compact size.

Yi-Pin Yang and I-ChenYang, K-Cherng Lin, K-Yi Lee, Yen-Juei Lin, Wei-Yu Lee **[19]**

In this paper the authors proposed a layout for designing all optical logic AND gate based on photonic crystal in 2D triangular lattice. It has two input port and one output port. This proposed structure composed of photonic crystal ring resonator (PCRR) waveguide sandwiched between two input waveguides. The field distribution is analyzed by FDTD method. The optical logic AND gate can function at different wavelength in the communication C –window (1530-1565 nm). This proposed design findings many of the applications in multi wavelength optical logic circuits.

Yulan.Fu, Xiaoyong.Hu, Qihuang Gong **[20]**

In this paper, the author used light beam interference effect in realization of all optical logic gates such as NOT, OR, NAND, XOR and XNOR based on 2D PhCs. All gates realize on controlling over optical path difference and maintaining the phase difference between the inputs in such way that they results in perfectly constructive and destructive interference for obtaining high intensity and low intensity respectively at the output. High intensity at the output can be considered as logic high level and low intensity considered as logic low level. In this paper contrast ratio mathematically calculated a maximum value of 20 dB. These logic gates do not required high power for their logical operations. This design offers an effective and a simple approach for the realization of integrated all-optical logic devices.

Preeti Rani, Y Kalra, R.K.Sinha **[21]**

The authors presented a layout design of logic AND gate based on photonic crystal in 2D triangular lattice or hexagonal lattice of air holes in Silicon substrate. This structure composed of a Y-shaped linear waveguide without using any external devices like semiconductor based optical amplifiers (SOAs). Operations function analyzed and simulated with plane wave expansion (PWE) and FDTD method respectively. The optimized parameters of this structure are determined which help in finding high contrast ratio to be obtained. Based on linear material there is low power consumption. The contrast ratio (CR) of this device is calculated to a value of 6dB for this proposed structure. This design finds its application in realizing optical devices and components for optical communication system and networks. This structure can be use for large scale integration (LSI) and also can be used in on chip photonic ICs.

C.Jung Wu, Chung Ping Liu, Zhengbiao Ouyang **[22]**

In this paper an optical logic NOT gate with low power consumption and having compact size is introduced based on PhCs waveguide without using any nonlinear materials and SOAs. This device is analyzed using FDTD method. The author also gives a way of determining its model parameter. They calculate a contrast ratio of 24.73 dB with optimized parameters. In this paper operating bit rate of proposed logic NOT gates is obtained to a value of 2.155 Tbit/s, which is higher than basic electronic logic gates. Since no optical amplifier is used, hence the proposed structure has a compact size (7a × 7a, where 'a' is the lattice constant). This device has wide operating bandwidth which is favorable for developing multi wavelength parallel-processing optical logic systems and for LSI optical devices. It can be operated at very low power and has a relatively large bandwidth.

Enaul haq Shaik & Nakkeeran Rangaswamy **[23]**

In this paper, the authors propose T-shaped waveguide structure based on 2D PhCs for designing a XOR, NOT, and OR logic gates and as an AND gate with small modification in the radius of its directional rods at T junction of waveguide. The phenomenon of constructive and destructive phase interference is used in this paper. With these phenomena, it is defined logic '1' and logic '0' for logical operations of gates. Constructive phase interference results in high intensity of light signals which is consider as logic '1' and destructive phase interference results in low light intensity read as logic '0'. These all optical logic gates are numerically analyzed by PWE and FDTD method in C-Band. In this paper, the author determined the ON to OFF contrast ratio (CR) of XOR and NOT gates is 54.91 dB while 6.02 dB for AND gate, with a fast response time of less than 0.15 ps. This proposed model allows logic gates to be utilized as a basic component in the future Photonic ICs with fast output response.

F.Parandin, Mohammad Mehdi Karkhanehchi **[24]**

In this paper, a new design of NOR and AND optical logic gates has been proposed based on 2D PhCs and the PWE and FDTD methods are used in the determination and simulation of the proposed structure. The proposed logic gates have compact size and are simple in designing. On Comparison with previous design of NOR and AND logic gates based on photonic crystals, the proposed logic gate in this paper enjoys proximity of the E-field output in "1" ("0") logic state, in relation to the input field of the source in the ON (OFF) state. This specification enables this proposed structure to be used in compact optical ICs. Also, a response time about 0.65 ps and bit rate of about 1.54 Tbit/s obtained for optical gates.

Preeti Rani, Y Kalra, R.K.Sinha **[25]**

In this paper, the authors design all optical logic gates based on 2D photonic crystals (PhC) triangular lattice of air holes in silicon.

The proposed structure has been simulated using finite difference time domain (FDTD) method and PWE method and it has been shown that all optical logic operations can be observed by introducing a proper initial phase between the input light signals so that they may interfere constructively or destructively. The proposed designed structure optical logic gates have a response period of 1.024 ps and can operate at a bit rate of 0.976 Tbit/s. In this paper, the author determined the ON to OFF contrast ratio (CR) of XOR gate to a value of 8.49 dB and NOT gates 5.42 dB while it is 8.76 dB for AND gate. This proposed model allows logic gates to be utilized as a basic component in the future Photonic ICs with fast output response.

CHAPTER 3

Numerical Methods

This chapter introduced about mathematical tools to analyze the output performance of the designed structure. Basically there are two method used for analysis of 2D PhCs based structure. The two methods are

1. Plane wave expansion (PWE) method.
2. Finite difference time domain method.

PWE method solves the Maxwell's equations in frequency domain and the second method FDTD solves the Maxwell's equation in time domain.

In this chapter firstly we introduce Maxwell's equations and then their solution in frequency and time domain.

3.1 Maxwell's Equations

EM wave propagation through PhCs is given by Maxwell's four equations. In a source free region these equations can be arranged as follows [15]:

$$\nabla \times H - \frac{\partial D}{\partial t} = J \tag{3.1}$$

$$\nabla \times E + \frac{\partial B}{\partial t} = 0 \tag{3.2}$$

$$\nabla \bullet B = 0 \tag{3.3}$$

$$\nabla \bullet D = \rho \tag{3.4}$$

Where

$\boldsymbol{E}$: E- Field Intensity
$\boldsymbol{H}$: Magnetic Field Intensity
D: E- Field Density
B: Magnetic Field Density
J: Current Density
ρ: Free Charge Density

3.2 PWE Method

Plane wave expansion method [15, 26-27] is widely used for getting dispersion relation and mode profiles inside PhCs structures. PWE gives a graph between frequency (f) v/s wave vector (k). This is a frequency domain method in which Bloch theorem is used for solving the Eigen value problems and solutions to these problems are obtained as a superposition of plane waves.

3.2.1 Solutions of Maxwell's Equations in Frequency Domain

For isotropic, linear, dispersive and transparent materials, the magnetic field density and electric field density is related to magnetic and electric field respectively through the following equations:

$$B = \mu_r \mu_0 H \tag{3.5}$$

$$D = \varepsilon_r \varepsilon_0 E \tag{3.6}$$

Where μ_r and ε_r are the relative permeability and relative permittivity of the material respectively. μ_0 Is equal to $4\pi\times10^{-7}$ Henry/m and ε_0 is 8.854×10^{-12} Farad/m in the vacuum permeability and permittivity respectively.
Now assumed that there is no free charge or current in the structure so ρ=0 and J=0.
With all the above assumptions and relations, the Maxwell's equations [3.1 - 3.4] can be rewritten as:

$$\nabla \times H = \varepsilon_r \varepsilon_0 \frac{\partial E}{\partial t} \tag{3.7}$$

$$\nabla \times E = -\mu_r \mu_0 \frac{\partial H}{\partial t} \tag{3.8}$$

$$\nabla \bullet H = 0 \tag{3.9}$$

$$\nabla \bullet E = 0 \tag{3.10}$$

The electric and magnetic field are function of space and time. The Maxwell's equations are linear so the dependence of time can be separated from the dependence of spatial by expanding E and H fields into a set of harmonic modes. Harmonic modes can be written as a mode profile times a complex exponential as below:

$$H(r,t) = H(r)\exp(-\mathrm{i}\,\omega\,\mathrm{t}) \tag{3.11}$$

$$E(r,t) = E(r)\exp(-i\omega t) \tag{3.12}$$

Curl equations (3.7) and (3.8) which are relating electric and magnetic fields can be written as

$$\nabla \times H(r) + i\omega\varepsilon_r\varepsilon_o E(r) = 0 \tag{3.13}$$

$$\nabla \times E(r) - i\omega\mu_o H(r) = 0 \tag{3.14}$$

Now we divide Equation (3.13) by ε_r and then take the curl we have

$$\nabla \times \left(\frac{1}{\varepsilon_r} \nabla \times H(r) \right) + i\omega\varepsilon_o \nabla \times E(r) = 0 \tag{3.15}$$

Using Equation (3.14) in above equation, we have

$$\nabla \times \left(\frac{1}{\varepsilon_r} \nabla \times H(r) \right) = \omega^2 \varepsilon_o \mu_o H(r) \tag{3.16}$$

Putting, $c = \frac{1}{\sqrt{\varepsilon_o \mu_o}}$ we get,

$$\nabla \times \left(\frac{1}{\varepsilon_r} \nabla \times H(r) \right) = \left(\frac{\omega}{c} \right)^2 H(r) \tag{3.17}$$

Similarly, we can write equation for electric field

$$\frac{1}{\varepsilon_r} \nabla \times \left(\nabla \times E(r) \right) = \left(\frac{\omega}{c} \right)^2 E(r) \tag{3.18}$$

Equations (3.17) and (3.18) are the examples of Eigen value problems having $\left(\frac{\omega}{c}\right)^2$ as Eigen values. One of these equations is solved to obtain the Eigen-frequencies for given dielectric constant ε_r . Eigenvectors corresponding to the Eigen-frequency give the information about the mode profile.

3.3 FDTD Method

To solve electromagnetic problems, FDTD method was proposed by Kane Yee in the year 1966. Various improvements to the novel Yee's algorithm have been presented since then for increasing the strength and accuracy. Yee's formulism which is best suited for the problems of electromagnetic wherein Maxwell's curl equations are solved in time domain to provide straightforward solutions.

CHAPTER 4

Design of Optical Logic XOR, OR, NOT Gate Based On 2D PhCs Waveguide Structure

4.1 Introduction

Now days demand for high speed and low power consumptions computing system increases day by day. In previously designed computing system, high power consumption and low speed is disadvantageous for optical communication system. As days passes researchers move on to optical logic gates where optical to electrical and electrical to optical conversion not required. Due to this, the speed of computing system increases and also required low power consumptions. Due to lack of conversion the speed of the systems improved and photon is a media for fast transmission data. This device can handle large bandwidth and information rate [1]. Optical gates proved very efficient components in computing system and to be used in many telecommunication systems as encoder, decoder, MUX, DEMUX, and also as switching devices. For designing optical logic gates there various methods based on optimized parameter which improves the results more and more. Logic gates may be designed with non-linear MZI, SOAs, PCFs, Fiber Bragg Gratings etc. But all these have some demerits like noise, low speed, large size, bandwidth and high response time etc. Photonic crystal a new type of material proved advantageous over all disadvantages in conventional designing. Some of its advantages are Light of particular wavelength range reflected by Photonic crystals which results in one mode of cavities unlike the metal cavities. All wavelengths reflected by the metal which results in infinite mode. Photonic crystals can withstand with high electric fields. The size of photonic crystal devices are in order of wavelength of light. Hence the devices are compact in size. Processes the data at high speed as the travelling speed in structure is speed of light. These devices protected to short circuits as well as noise as the information carriers are photons unlike electrons in metallic wires. Low power consumptions due to linear property of photonic crystal. Photonic crystals confine the light highly in the structure due to large difference present for effective index. PhC Controls the spontaneous emission in the lattice. In this chapter we introduced a new design to operate it as all logic gates. We proposed a T- shaped common structure with which we perform all logical operation such as XOR, NOT, OR, AND logic. In this structure we use concept interference for their logical operation. PhCs based logic gates much better than earlier design optical logic gates due to its unique properties of varying refractive index. In this photon play an important role for fast speed and low power consumptions of the logic gates.

In this thesis we observed that the contrast ratio improved than existing logic gates. In this chapter we presents the designing model and their simulation method for analyze the performance of designed logic gates. MMI based logic gates also provide high contrast ratio but their inputs are phase dependent which not provide cascading of logic function to upscale logical function.

4.2 Design and operating principle

PhC Controls the spontaneous emission in the lattice. In this chapter we introduced a new design to operate it as all logic gates. We proposed a T- shaped common structure with which we perform all logical operation such as XOR, NOT, OR, AND logic. In this structure we use concept interference for their logical operation.

A t-shaped waveguide structure is design as common structure for logic XOR, NOT, OR gates with having optimized parameters. Design is based on the principle of interference. There are two inputs port and one output port. If the signals launched at the inputs ports results in constructive interference then a high light intensity is obtained at output port. High light intensity can be considered as low logic function (Logic 1). When signals launched at input ports results in destructive interference then a low light intensity is obtained at output port. This low light intensity is considered as a high logic function (Logic 0). Thus we can say that the design is based on principle of light interference phenomenon. The signals launched at input are a Gaussian signal. There are two input one of which is used as reference input for logic NOT gate because logic NOT is a single input function. When there is no signal is launched then reference input comes in role. Reference input in NOT gate is applied with 180 degree phase.

Analysis parameter named as contrast ratio is defined for the performance of logic gates. It is defined as the ratio of average power at output port for high logic function to the average power for low logic function. Mathematically it can be given as below formula;

$$CR = 10 \log \frac{P_1}{P_0} \qquad 4.1$$

Where,

P_1 and P_0 are output average for high and low intensity at output port. It is measured in dB always.

The structure consists of an array of size 21 × 15 rods of *Si* material with having a refractive index of value 3.46 and radius of value 0.2*a*, where '*a'* is named as lattice constant and have value of 600 nm.

All designing parameters of this structure are mentions below in Table 4.1

Parameters	**Numerical Values**
Dielectric rods	Silicon (*Si*)
Array size	15×21
Refractive index of dielectric rods	3.46
Radius of rods	0.2a
Lattice constant 'a'	600 nm

Table 4.1 Structural Parameter of Proposed Logic Gates in PhCs

The design of proposed structure is shown in below Fig 4.1

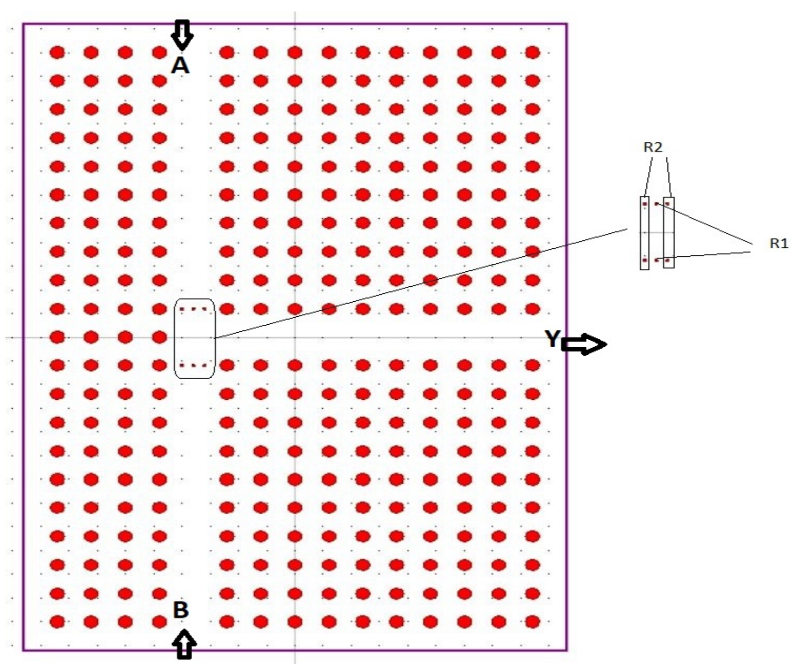


Fig. 4.1 Proposed logic gates structure based on PhCs lattice

As we observed from the figure 4.1 that it is a t-shaped waveguide created in 2D PhC in square lattice and all the three branches is of same length.

There are two inputs port A and port B and one output port Y. At its t-junction there are 6 extra rods known as directional rods which are helpful to direct light from input ports. These rods created defect in the 2D structure which makes possible light to travel. Without creating defects light not passes through t-junction.

The rods *R1 and R2* is obtained to be a value of 25 nm for XOR, OR, NOT functions where it is different for AND logic gate discuss in next chapter 5. The Photonic Band Gaps (PBGs) of t-shaped waveguide are obtained by using PWE method. The PBG shown in Fig. 4.2 describes band gaps. As the figure show, there are two bands for TE modes, among which wider window is chosen which fall into communication window. This band have wavelength range of value 1440 nm to 2120 nm i.e. 0.282568 (*a/λ*) to 0.416924 (*a/λ*)). At this wavelength light is get reflected back via the PhCs.

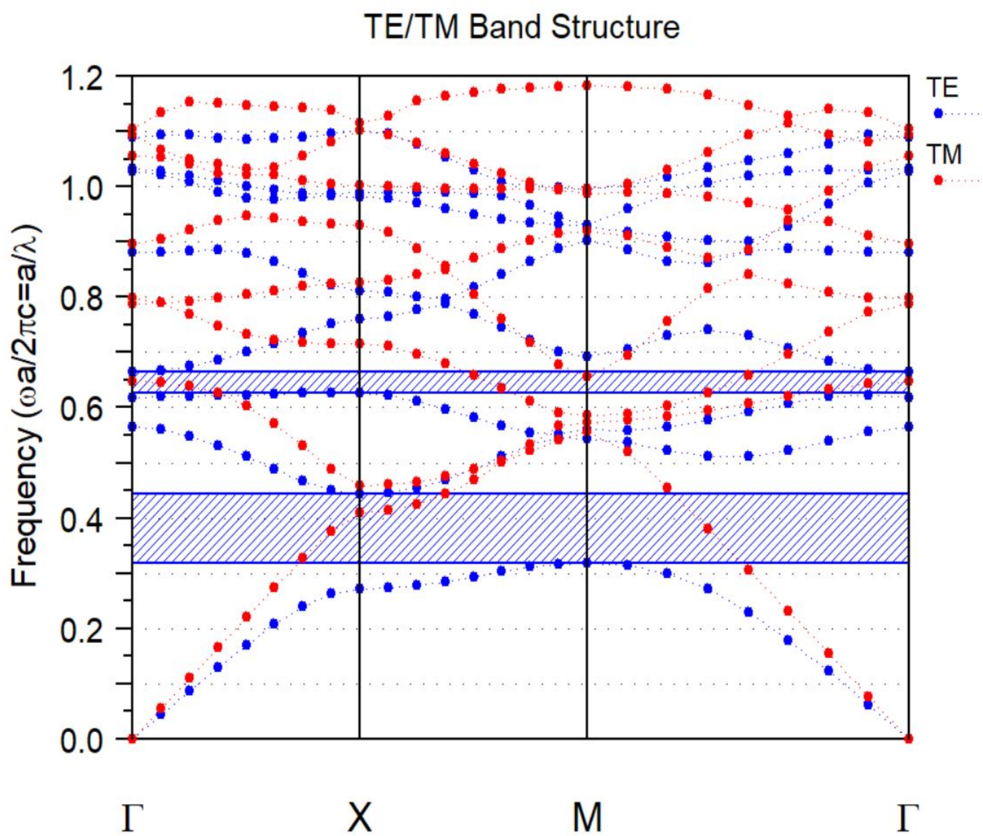


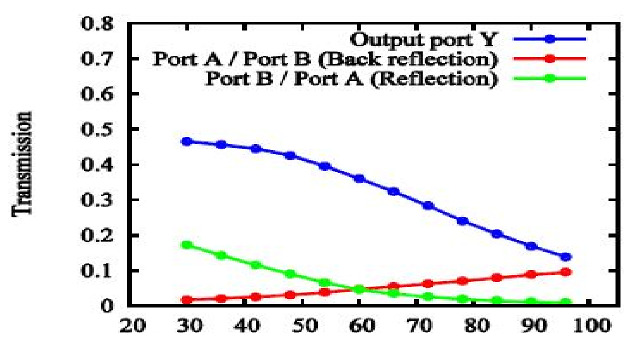
Fig. 4.2 Band Diagram of 2D PhC for Define Parameters

Binary logic function i.e. high logic function and low logic function at the input and output of designed structure may be defined based on intensity of light. Light interference at t-junction of structure depends on phase difference of light signals launched at inputs port. The desired output is achieved by light interference at t-junction.

Since the path length of light signals launched at inputs port A and port B to reaches at t-junction is of same length we obtained constructive and destructive interferences at phase difference of zero degree and 180^0 degree. Constructive behavior of signals at t-junction defined high level logic and destructive behavior defined low level logic. For OR logic function, both signal at port A and port B launched with zero degree phase that results the constructive nature interference at the output and can be observed a high light intensity at output port. And high light intensity at output defined high level logic. Similarly for XOR logic functions both the inputs are launched at a phase difference of having 180^0 phase. For this condition both signal meeting at junction results in the destructive nature interference at the output port. For destructive interference we observed a low light intensity at output. And this low light intensity at output port defined low level logic function for XOR. The same constructive and destructive interference principle will be applied for NOT logic operation. As we discuss above that optical NOT logic function uses an extra input known as reference input port B. This reference input launched at phase of 180^0. In optical logic gates reference input used to get output when input signal is not launched for logic gates like, NAND and XNOR logic gate. For NOT logical operation, input port A is launched with 0 degree phase and port B launched with reference input signals of have 180 degree phase. This inputs signal launched at input port meets at junction and results in destructive interference at output for NOT gate. Due to destructive interference we observed a low light intensity at output port Y. This low intensity at output defined low level logic for NOT logic operation.

Now we study the role of directional rods at t-junction. These directional rods at t-junction basically create a cavity in PhCs that is helpful to light signals launched at inputs port. As we discuss previously that without breaking the periodicity of PhCs light signals with wavelength which falls in photonic band cannot pass through the PhCs. So to allow light signals pass through PhCs, we need to break the periodicity of PhCs. These directional rods helpful in breaking the periodicity of it and direct the light signal to the output port. To get proper output transmission we need to optimize the radius of these rods. Before we optimized radius of these rods we need to understand some basic definitions like reflection and back reflections. The reflection can be understand as a leakage to non-excited input ports where as back reflection is light reflected to excited input ports.

The results of optimized radius of directional rods is shown in below Fig 4.3,



Radius of rod R1

Fig 4.3 Effect of radius of rod R1

The above figure shows the graph between output transmission and the radius of rod R1. From Fig 4.3 we observed that as the radius of rod R1 increases back reflection at inputs port A and B increased. As back reflection increases, the output transmission reduced. But increase in radius results in reduction of reflection i.e. leakage. When we launched signal at single input we have to be high light intensity at output port Y for logic operation of XOR, OR, NOT to define high level logic. Thus we obtained a value of 25 nm when a single input is launched for optical logic gates XOR, OR, NOT. On other hand it is optimized to 90 nm for AND gate logic operation.

4.3 Results and Discussions

4.3.1 XOR Gate

To understand the logical operation for XOR logic gate we need the concepts of interference phenomenon. For XOR logic gates, input port A is launched at 0 degree phase and port B is launched at 180 degree phase. This input signals combination has a phase difference of 180 degree. At t-junction they results in destructive interference and we get a low light intensity at output port Y. Low light intensity at output defined low level logic.

Similarly another input combination when no light signal is launched at input port A and port B is excited with a phase of 180 degree. This combination results in constructive interference at t-junction. Constructive interference results in high light intensity at output port Y. This high intensity defined high level logic at output port Y.

The same constructive interference will obtained for input combination when light signal is launched at input port A with phase of 0 degree and input port B is unexcited. In this case also we get a high intensity light at output port which defined high level logic at port Y.

For getting proper output transmission we need perfectly matched boundary conditions. Perfectly matched boundary conditions avoid reflection at the junction.

The EM wave propagates in the direction of X-Z plane with magnetic field polarizations in parallel with axis of the Silicon rods (Si) i.e. in *y*-axis.

In order to achieved perfectly matched condition, the space grids must be take care in such that

$$\Delta x < \frac{\lambda}{10}$$

$$\Delta z < \frac{\lambda}{10},$$

Where Δx and Δz are space grids in the direction of X-axis and Z-axis

For Stable simulations condition can be achieved by choosing Δx and Δz in such a way that the following Courant condition [12] can be satisfied,

$$c\Delta t < \frac{1}{\sqrt{(\Delta x)^{-2} + (\Delta z)^{-2}}}$$

We launched the signals at a wavelength of 1550 nm and simulate with the help of FDTD method.
For XOR logic operations, the fields' distribution and its output transmission for all 3 input combinations are shown in below Fig. 4.4

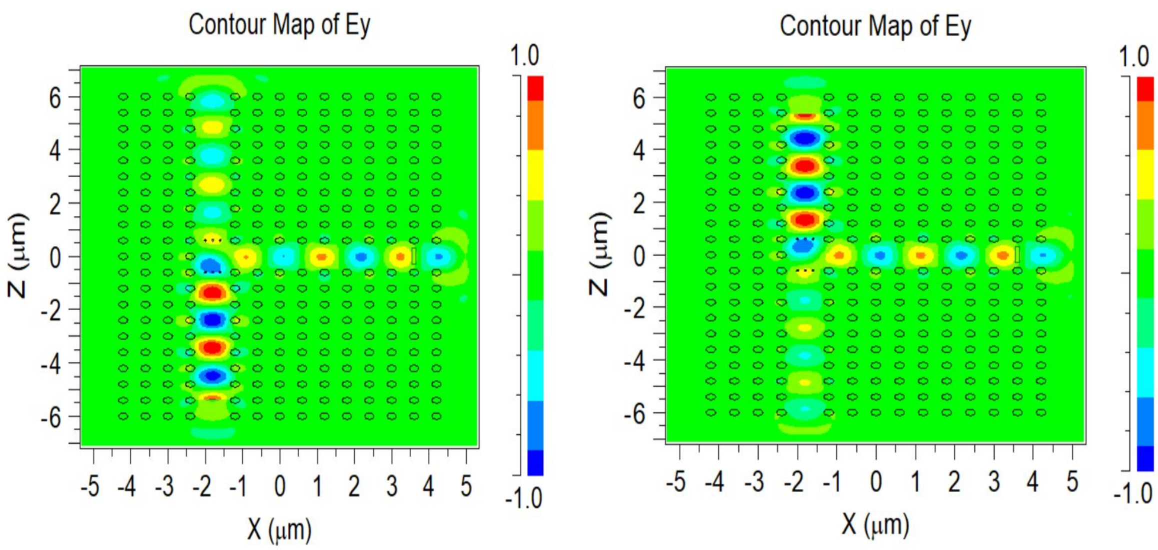


Fig 4.4 (a) Optical Field Distribution of XOR Gate for input A=0 & B=1 and A=1 & B=0

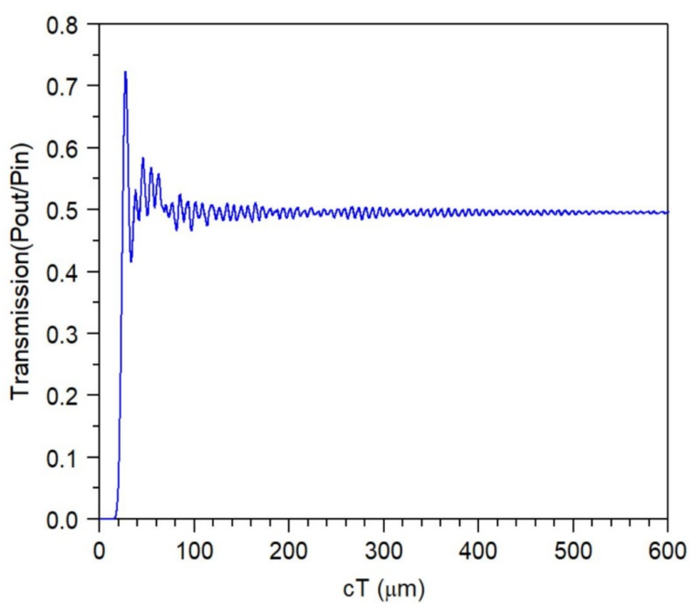


Fig 4.4 (b) Output Transmission of XOR Gate for input A=0, B=1 & A=1, B=0

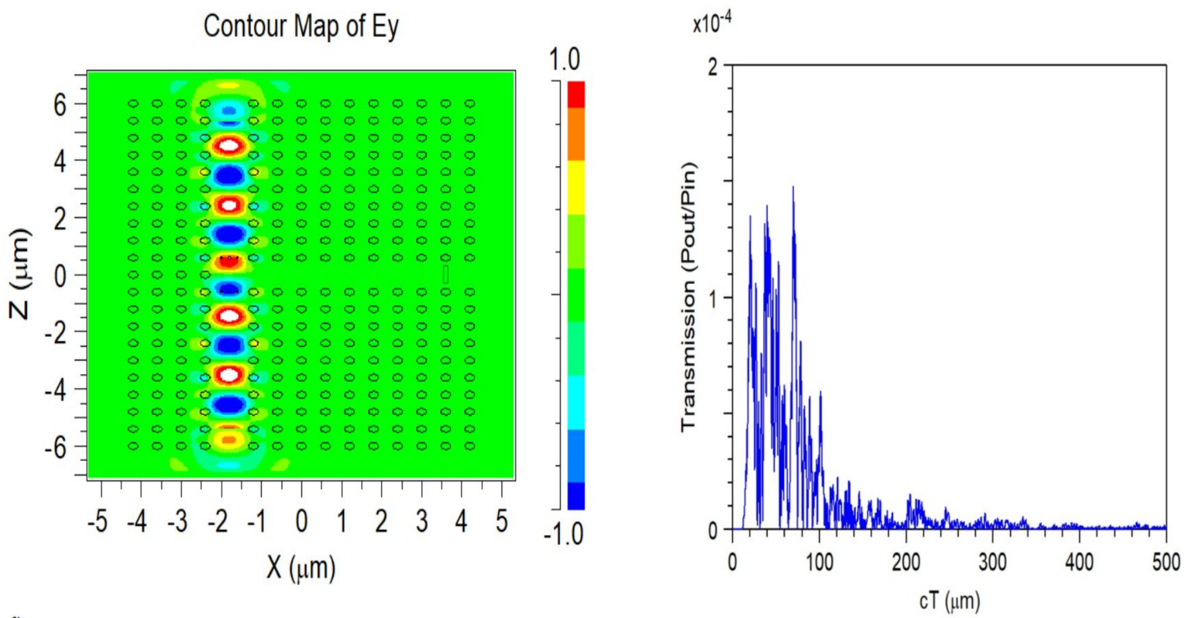


Fig 4.4 (c) Optical Field Distribution & Output Transmission for XOR Gate for input A = 1 & B = 1

As the Fig 4.4(a) shows field distribution when light signal launched at either the port B or port A. In this input combination the directional rods at t-junction absorb some amount of light and the remaining part of light signals pass through the t-junction which can be observed at output port Y. In this condition constructive interference causes to high light intensity at output port which defined as high level logic. For this optical field distribution, the output transmission is shown in Fig 4.4 (b).

Fig 4.4 (b) shows the output transmission for XOR which conclude that the output transmission (Pout/Pin) at output port *Y* is observed to a value of 0.49, which is considered as high level logic. When light signal at either of the inputs port i.e. either at port A or port B is launched they results in constructive interference at junction. This constructive interference result in high light intensity at output port Y. High light intensity at output defined high level logic.

Fig 4.4 (c) shows field distribution and output transmission for XOR logic operation when both the input ports are launched. When light signal at input port A and port B is launched they results in destructive interference at junction. For this input combination a low light intensity is obtained which defined low level logic function. And at the output port Y the output transmission is obtained to a negligible value of 0.00000142.

The all above three cases can be summarized in the below Table 4.2

Input		XOR Gate		
Port A (ϕ)	Port B (ϕ)	Output Transmission	Logic	Contrast Ratio (dB)
0	0	0	0	55.38
0	1(180^o)	0.49	1	
1(0^o)	0	0.49	1	
1(0^o)	1(180^0)	0.00000142	0	

TABLE 4.2 A Summary on Performance Analysis of XOR Gate

As we defined contrast ratio earlier we can find the value of contrast ratio by observing above table. The contrast ratio is defined for the performance of logic gates. It is defined as the ratio of average power at output port for high logic function to the average power for low logic function. Mathematically it can be given as below formula;

$$CR = 10\log\frac{P_1}{P_0}$$

From the table by putting the value of P_1 and P_0 in above formula we calculate contrast ratio (CR) a value equal to 55.38 dB.

4.3.2 NOT Gate

As we discuss that optical NOT logic function uses an extra input known as reference input port B. This reference input launched at phase of 180^0. For NOT logical operation, input port A is launched with 0 degree phase and port B launched with reference input signals of have 180 degree phase. This inputs signal launched at input port meets at junction and results in destructive interference at output for NOT gate. Due to destructive interference we observed a low light intensity at output port Y. This low intensity at output defined low level logic for NOT logic operation. When input port A is unexcited and port B is launched with light signal with phase 180 degree, high light intensity is obtained at output port Y. High light intensity at output defined high level logic in this input combination.

For NOT logic operations, the fields' distribution and its output transmission for the input combinations are shown in below Fig. 4.5

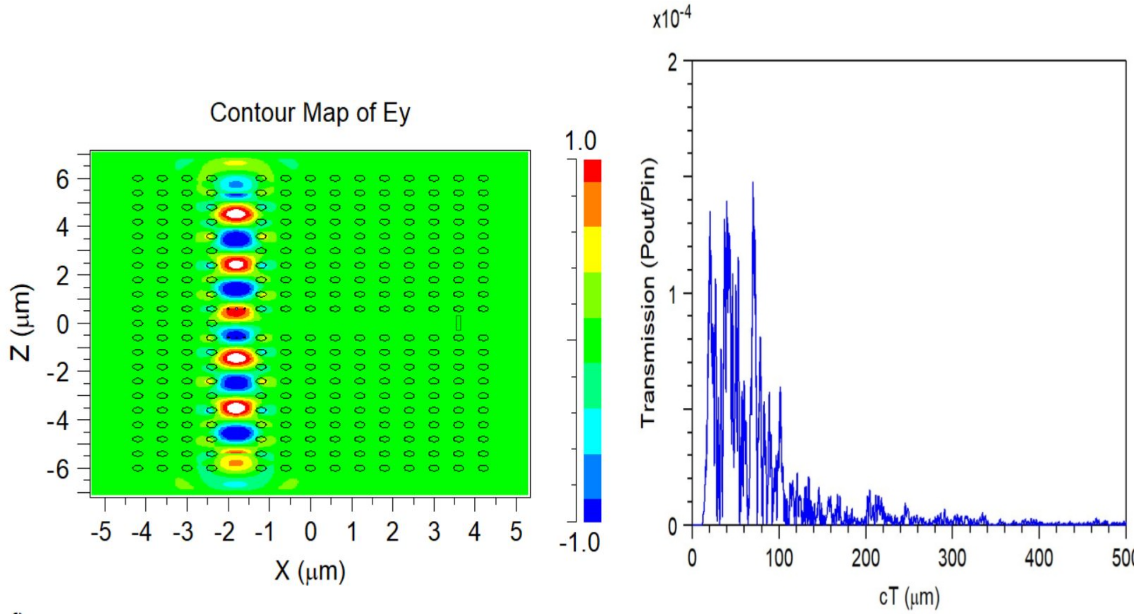


Fig 4.5 (a) Field Distribution & Output Transmission for NOT logic Gate
For input A = 1

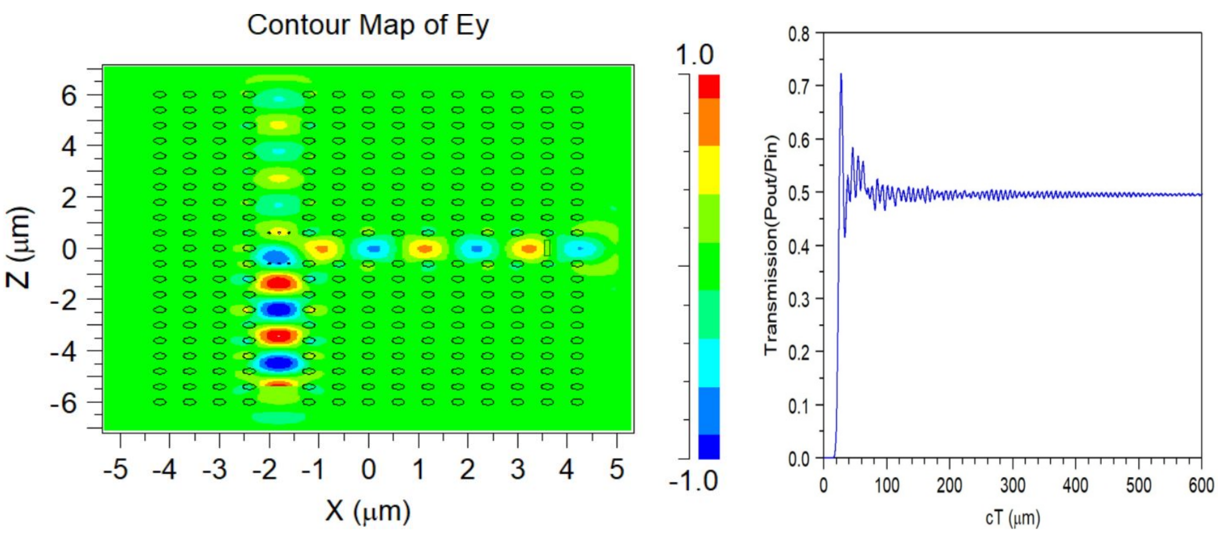


Fig 4.5 (b) Field Distribution & Output Transmission for NOT Gate
For input A = 0

Fig 4.5 (a) shows the field distribution & transmission output when input port A is launched with 0 degree phase and signal launched at input port B have phase 180 degree. This inputs combination results in destructive interference at t-junction. Destructive interference produced a low level light intensity at output port Y. This low light intensity defined low level logic at output. The output transmission has a negligible value equal to 0.00000142.

Fig 4.5 (b) shows the field distribution & transmission output when input port A is unexcited and signal launched at input port B have phase 180 degree. This inputs combination results in constructive interference at t-junction. Constructive interference produced a high level light intensity at output port Y. This high light intensity defined high level logic at output. The output transmission has a value equal to 0.49.

The above two cases of NOT logic operations can be summarized as below Table 4.3

Inputs	NOT Logic Gate		
A (ϕ)	Output Transmission	Logic	Contrast Ratio (dB)
0	0.49	1	55.38
$1(0^0)$	0.00000142	0	

TABLE 4.3 Summary on Performance Analysis of NOT Gate

For this logic gate also we can calculate contrast ratio as the ratio of average power at output port for high logic function to the average power for low logic function.
Mathematically;

$$CR = 10\log\frac{P_1}{P_0}$$

From the table by putting the value of P_1 and P_0 in above formula we calculate contrast ratio (CR) a value equal to 55.38 dB.

4.3.3 OR Gate

For OR logic function, both signal at port A and port B launched with zero degree phase that results the constructive nature interference at the output and can be observed a high light intensity at output port. And high light intensity at output defined high level logic.
For OR logic operations, the fields' distribution and its output transmission for the input combinations are shown in below Fig. 4.6

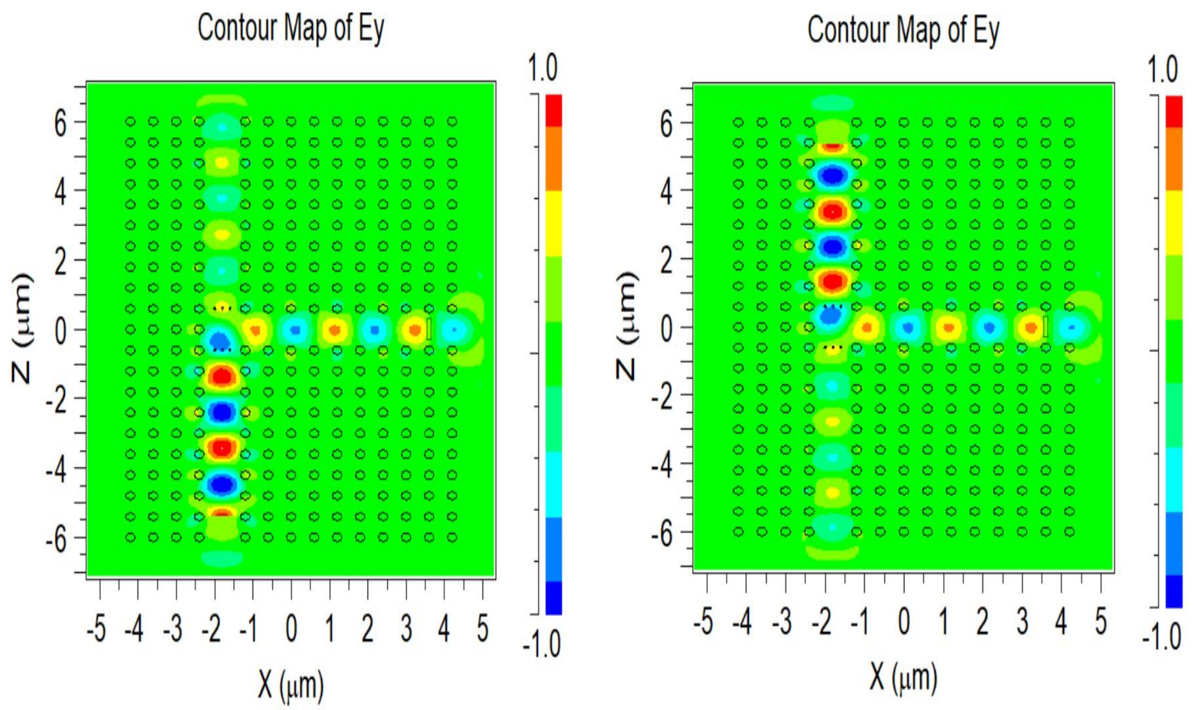


Fig 4.6 (a) Optical Field Distribution of OR Gate for A=0, B=1 & A=1, B=0

As the Fig 4.6(a) shows field distribution when light signal launched at either the port B or port A. In this input combination the directional rods at t-junction absorb some amount of light and the remaining part of light signals pass through the t-junction which can be observed at output port Y. In this condition constructive interference causes to high light intensity at output port which defined as high level logic. For this optical field distribution, the output transmission is shown in Fig 4.6 (b).
Fig 4.6 (b) shows the output transmission for OR which conclude that the output transmission (Pout/Pin) at output port *Y* is observed to a value of 0.49, which is considered as high level logic. When light signal at either of the inputs port i.e. either at port A or port B is launched they results in constructive interference at junction. This constructive interference result in high light intensity at output port Y. High light intensity at output defined high level logic.

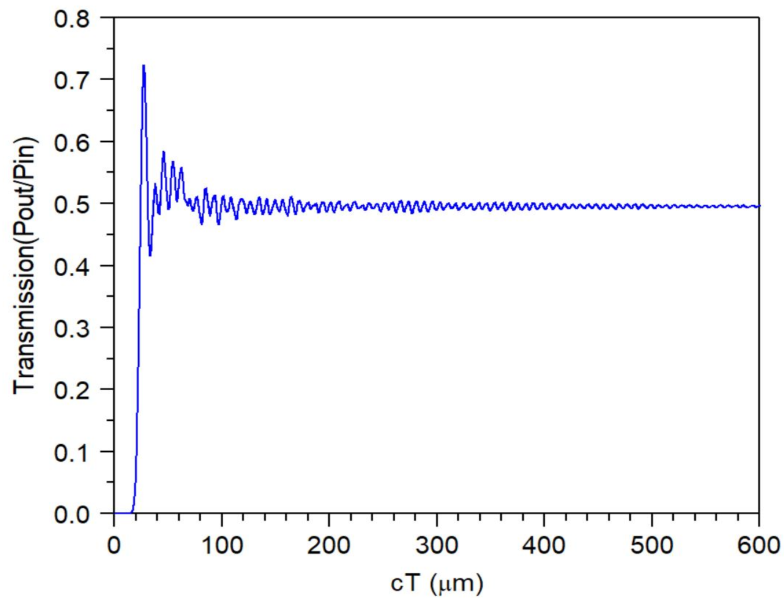


Fig 4.6 (b) Output Transmission for OR logic Gate for input A=0, B=1 & A=1, B=0

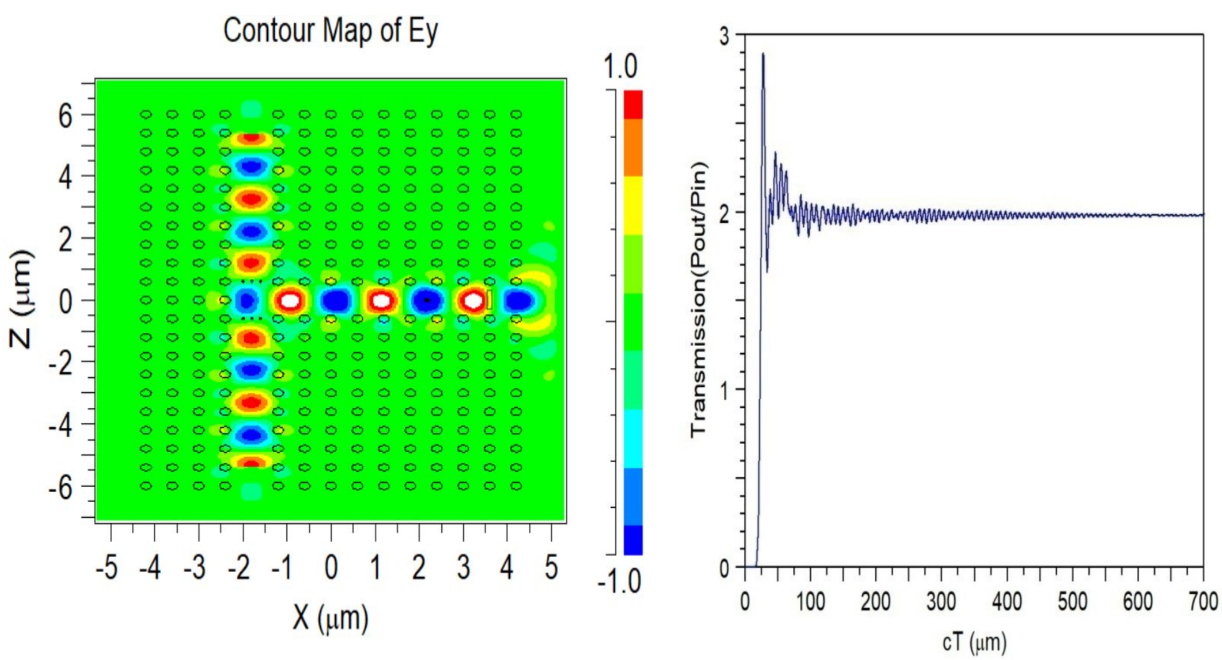


Fig 4.6 (c) Field Distribution & Output Transmission for OR Gate for input
A = 1 & B = 1

Fig 4.4 (c) shows field distribution and output transmission for OR logic operation when both the input ports are launched. When light signal at input port A and port B is launched they results in constructive interference at junction.

This constructive interference result in high light intensity at output port Y. High light intensity at output defined high level logic. The output transmission has a value equal to 1.97
All input combinations performance of OR logic function can summarized in below Table 4.4

Inputs		OR logic Gate	
A (ϕ)	B (ϕ)	Output Transmission	Logic
0	0	0	0
0	$1(0^0)$	0.49	1
$1(0^0)$	0	0.49	1
$1(0^0)$	$1(0^0)$	1.97	1

TABLE 4.4 A Summary on Performance Analysis of OR Gate

4.4 Response Time Calculation of Logic Gates

Fig 4.7 shows the time evolving curve for designed common structure for optical XOR, OR and NOT logic gates. This curve show optical transmission output for Logic'1' in case of all three gates, with the help of this curve we can calculate time response for optical logic gates. From the fig 4.7, we observed that total time (*T*) required for the proposed design structure to reach the output from 0 to 90% of the average output power P_{avg} is 0.0875 ps *(cT = 26.25μm),* where *c* is the light speed $\left(3\times10^8 m/s\right)$. This total time (*T*) is consist of two components, transmission delay $\left(t_{11}\right)$ which is the time required by output to reach from 0 to 10% of the P_{avg}, and another one is the time $\left(t_{12}\right)$, the time required by output to reach from 10 to 90% of P_{avg}. From time evolving curve, we observed values of these two components calculated to a value of $t_{11} = 0.0646$ ps (19.39μm) and $t_{12} = 0.0229$ *(cT=6.862μm).* The falling time from P_{avg} to 10% of average output can be assumed to be same value as that of time $\left(t_{12}\right)$. This shows, the narrow pulse width is of $2 * t_{12} = 0.0458$ ps. Hence, a response time of 0.092 ps is determined for a complete period of 50% duty cycle.

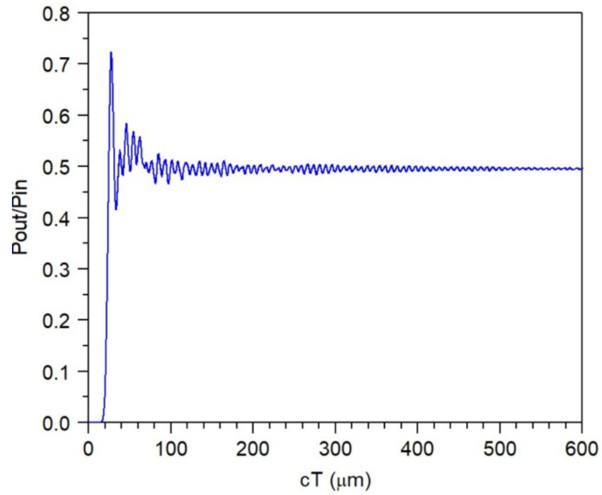


Fig. 4.7 Time evolving curve for the design structure for XOR, OR & NOT .logic gate.

CHAPTER 5

Design and Analysis of Logic AND Gate Based On 2D Photonic Crystals Modified Structure

5.1 Modified structure for AND Logic Gate and its operation principle

The proposed structure discussed in previous chapter 4 for Logic XOR, NOT and OR gate can also be used in designing a AND gate by small modification in radius of rod R1. Radius of rod R1 is optimized as 90 nm where as radius of rod R2 is same as 25 nm. Fig 5.1 shows proposed model for AND gate. The inputs should be applied in such a way that their phase difference results constructive interference between them at t-junction. This constructive interference results in high light intensity. High light intensity defined high level logic at port Y. As the radius of the rod R1 is larger it results increase in back reflection. As the back reflection light is more it causes to less amount of light intensity reach at output port Y. When light signal at input port A and port B is launched they results in constructive interference at junction. This constructive interference result in high light intensity at output port Y. High light intensity at output defined high level logic.

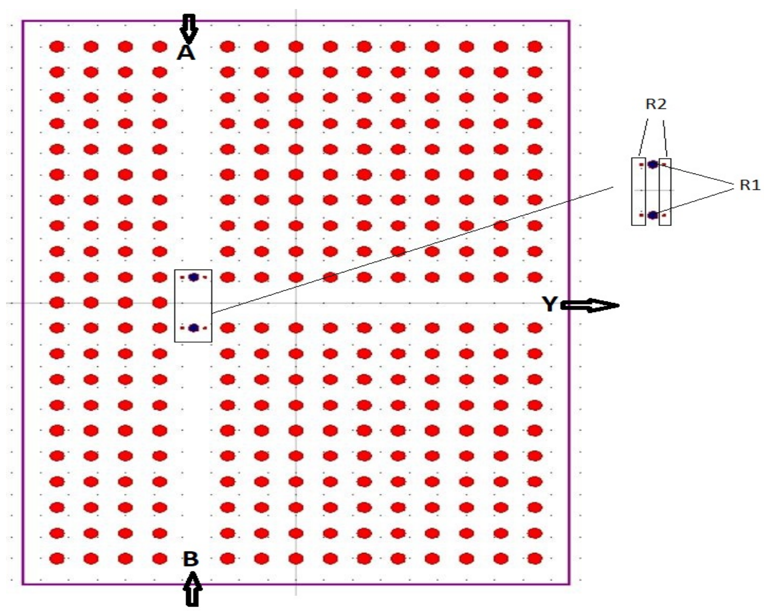


Fig 5.1 Modified structure for AND logic gate.

5.2 Results and discussions

For AND logic function, both signal at port A and port B launched with zero degree phase that results the constructive nature interference at the output and can be observed a high light intensity at output port. And high light intensity at output defined high level logic.

For AND logic operations, the fields' distribution and its output transmission for the input combinations are shown in below Fig. 5.2

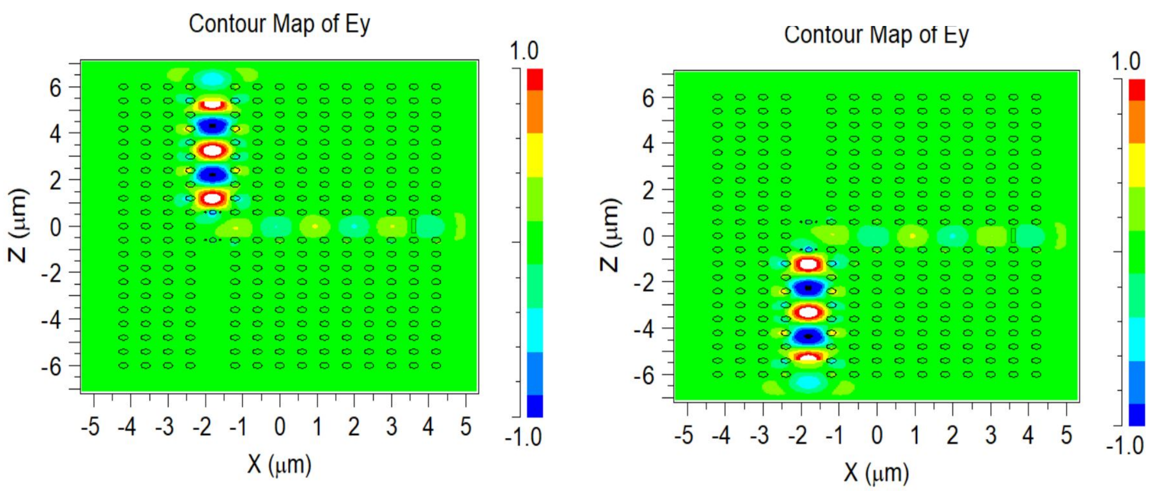


Fig 5.2 (a) Optical Field Distribution of AND Gate for A=0, B=1 & A=1, B=0

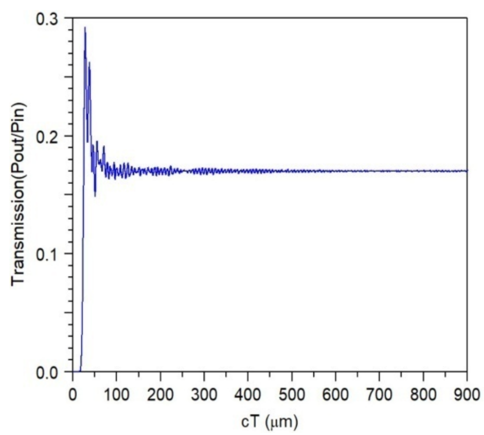


Fig 5.2 (b) Output Transmission for AND logic Gate for input A=0, B=1 & A=1, B=0

As the Fig 5.2 (a) shows field distribution when light signal launched at either the port B or port A. In this input combination the directional rods at t-junction reflects more amount of light back to the inputs ports and the remaining part of light i.e. a negligible amount of light signals pass through the t-junction which can be observed at output port Y. In this condition we get low light intensity at output port which defined as low level logic. For this optical field distribution, the output transmission is shown in Fig 5.2 (b).

Fig 5.2 (b) shows the output transmission for AND which conclude that the output transmission (Pout/Pin) at output port *Y* is observed to a value of 0.170, which is considered as low level logic. When light signal at either of the inputs port i.e. either at port A or port B is launched they get reflected back at junction. And a negligible amount of light signals pass through the t-junction which can be observed at output port Y. In this condition we get low light intensity at output port which defined as low level logic. High light intensity at output defined high level logic.

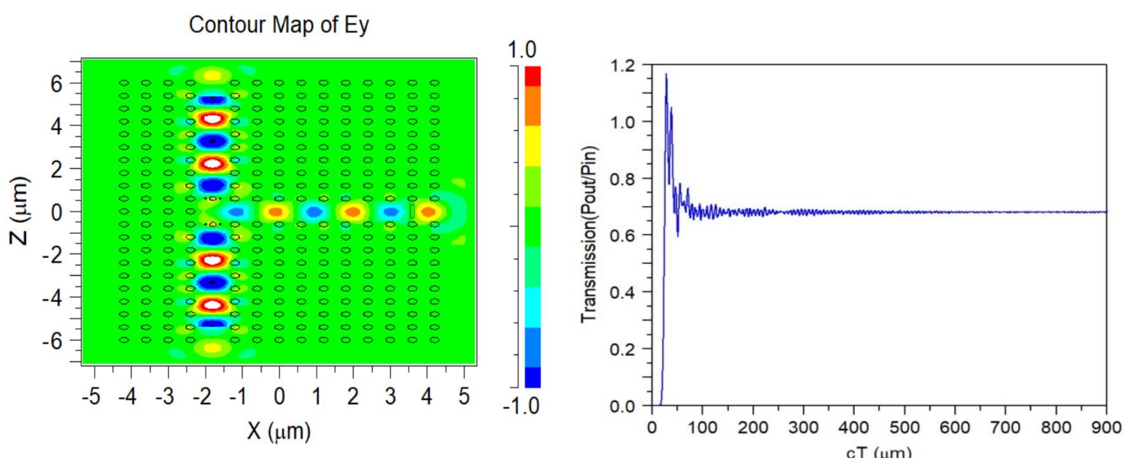


Fig 5.2 (c) Field Distribution & Output Transmission for OR Gate for input
A = 1 & B = 1

Fig 4.4 (c) shows field distribution and output transmission for AND logic operation when both the input ports are launched. When light signal at input port A and port B is launched they results in constructive interference at junction. This constructive interference result in high light intensity at output port Y. High light intensity at output defined high level logic. The output transmission has a value equal to 0.682

All input combinations performance of AND logic function can summarized in below Table 4.4

Input		AND logic Gate		
Port A (ϕ)	Port B (ϕ)	Output Transmission	Logic	Contrast Ratio (dB)
0	0	0	0	6.033
0	1(0^o)	0.682	1	
1(0^o)	0	0.682	1	
1(0^o)	1(0^0)	0.170	0	

Table 5.1 Summary on Logic Operation for AND gate

As we defined contrast ratio in Chapter 4, the contrast ratio is defined for the performance of logic gates. It is defined as the ratio of average power at output port for high logic function to the average power for low logic function. Mathematically it can be given as below formula;

$$CR = 10\log\frac{P_1}{P_0}$$

From the table by putting the value of P_1 and P_0 in above formula we calculate contrast ratio (CR) a value equal to 6.033 dB.

5.3 Response Time

The response time calculation is same as that of the previous chapter 4 from the time evolving curve shown in Fig 5.3.

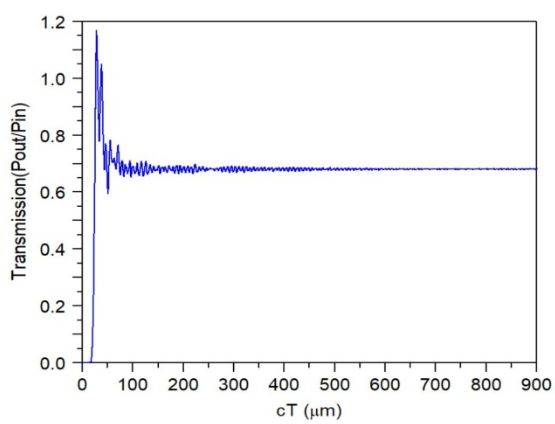


Fig 5.3 Time evolving curve for AND logic gate

From the Fig 5.3, we observed that total time (*T*) required for the proposed design structure to reach the output from 0 to 90% of the average output power P_{avg} is 0.0913 ps *(cT = 27.39 µm),* where *c* is the light speed $\left(3\times10^{8} m/s\right)$. This total time (*T*) consist of two components, transmission delay $\left(t_{11}\right)$ which is the time required by output to reach from 0 to 10% of the P_{avg}, and another one is the time $\left(t_{12}\right)$, the time required by output to reach from 10 to 90% of P_{avg}. From time evolving curve, we observed values of these two components calculated to a value of $t_{11} = 0.0709$ ps (21.26 µm) and $t_{12} = 0.0204$ *(cT=6.13 µm).* The falling time from P_{avg} to 10% of average output can be assumed to be same value as that of time $\left(t_{12}\right)$. This shows, the narrow pulse width is of $2*t_{12} = 0.0408$ ps. Hence, a response time of 0.082 ps is determined for complete period of 50% duty cycle.

CHAPTER 6

Conclusion and Future Work

This chapter summarizes the all work done in this thesis till now. First conclusions have been made from this study and then the future scope related to topic of this thesis is discussed.

6.1 Conclusion

This thesis reports a successful design and simulation of all optical logic gates based on 2D Photonic crystal square lattice with the help of Rsoft. The designed structure uses light interference phenomenon for the logic operation of all optical gates. The optical parameters of proposed structure and properties of PhCs are analyzed. With the help of a common proposed waveguide structure various number of logic functions (AND, OR, XOR and NOT) were realized only by varying reference input. These optical logic gates have a simple structure and may be integrated along with all optical devices such lasers, couplers, amplifier and limiter on a single chip. Further all optical arithmetic logic functions may be integrated on the same PhC substrate. PIC provides high density integration of optical components because of its unique properties.

This chapter concludes all the results we obtained. As we defined all objective goals of this thesis in first chapter and we obtained the same results. We get a successful design for all optical logic gates. To analyze all logical operation we used FDTD method as simulation tools. All simulations are done by using the Rsoft. The Rsoft is very efficient tools to analyze the output by FDTD method.

In chapter 4 we discuss a common structure for optical logic gates XOR, NOT, OR. The same proposed structure can also be used in designing optical AND logic gate with small modification in radius of directional rods at t-junction discussed in chapter 5.

Proposed designs work on the principle of interference between the light signals launched at two input ports. In the proposed model for designing optical logic gates there are two inputs port, port A and port B. And one output port Y. In the designing of NOT gate, port B used as reference input with a phase of 180 degree. In optical OR logic gate, the phase difference between the inputs is 0 degree and same phase difference in optical AND logic gate is optimized between the light signals launched at inputs.

The phase difference is optimized 180 degree between the light signals launched at inputs in the case of optical XOR and NOT logic gates. And we calculate contrast ratio of value equal to 55.38 dB which shows an improvement in the contrast ratio in the comparison of recent designed optical logic gates.

For optical AND logic gate we calculate contrast ratio of value equal to 6.033 dB which is greater the value of contrast ratio in literature.
From the time evolving curve we observed output response time of 0.082 and 0.092 for AND logic gate and XOR, OR, NOT logic gates respectively.
Comparison of designed logic functions in this thesis with various designs in literature survey can be concluded in Table 6.1 as follow:

Logic gates design in the literature survey	**Design Gates**	**Contrast Ratio (dB)**	**Response Time(ps)**
P.Rani, Y Kalra, R.K Sinha., 2013	AND	6.017	1.204
Wu et al., 2012	NOT	24.73	0.464
P.Rani, Y Kalra, R.K Sinha., 2015	AND	8.76	1.024
	OR	--	
	NOT	5.42	
	XOR	8.49	
Shaik et al., 2017	AND	6.02	0.1428
	OR	--	0.1344
	NOT	54.91	
	XOR	54.91	
Proposed work	AND	6.033	0.082
	OR	--	0.092
	NOT	55.38	
	XOR	55.38	

Table 6.1 Comparison of Designed Logic Functions with Various Designs in Literature

6.2 Future Work

Now days the computer industry is looking an innovative designing of computing technology to meet the growing demand for low power consumption and high speed computing system. This thesis suggests an idea for more complex computing optical devices such as FA & FS, HA & HS, an arithmetic unit, encoder and decoder, MUX and DEMUX etc. Fabrication of proposed PhC logic gates and PIC will be made possible in near future with the advanced semiconductor fabrication technology.

In future proposed design parameter further can be improved for better performance of all optical logic gate. The contrast ratio further can be improved by appropriate selection of optical wavelength which results in more compact size of design and chip density may be increased. More fast computing system may design with the help of 2D photonic crystal in near future.

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