Design and performance analysis of 2-D Photonic Crystal all Optical Logic Gate

A thesis submitted

by

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Certificate

This is to certify that the thesis entitled **Design and performance analysis of 2-D Photonic Crystal all Optical Logic Gate** which is submitted by **VISHAKHA SAINI (2017PWC5431)** in partial fulfillment of requirement for degree of Master of Technology in Wireless & Optical Communication Engineering submitted to **Malaviya National Institute of Technology, Jaipur** is a record of student own work carried out under my supervision. The matter in this report has not been submitted to any university or institution for the award of any degree.

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Declaration

I, VISHAKHA SAINI, hereby declare that this thesis submission titled as analyze the performance of 2-D photonic crystal based all optical logic gate , is my own work and that, to the best of my knowledge and belief.

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VISHAKHA SAINI

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-Vishakha Saini

List Of Abbreviations

1D - 1 Dimension

2D - 2 Dimension

3D - 3 Dimension

SOA - Semiconductor optical amplifier

Si - Silicon

Ge - Germanium

PhC - Photonic Crystal

PCRRs - photonic crystal ring resonators

MZI - Mach Zehnder Interferometer

PBG - Photonic Bandgap

RI - Refractive Index

EM - Electromagnetic Wave

TE - Transverse electric

TM - Transverse magnetic

PIC - Photonic Integrated Circuit

TIR - Total Internal Reflection

SHG - Second Harmonic Generation

OLNG - optical logic NOT gate

OPA - Optical Parametric Amplification

SPM - Self Phase Modulation

XPM - Cross Phase Modulation

PWE - Plane Wave Expansion

FDTD - Finite difference time domain

E - Electric Field

List Of Symbols

μm - Micrometre

ζ - Kerr Coefficient

n - Refractive Index

P_{in} - Power at input

P_{out} - Power at output

λ - Wavelength

a - Lattice constant

nm - nanometer

$\pm$ - plus minus

$2.5 * A$ - Free space wavelength

ϵ - vacuum permittivity

χ - susceptibility

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Abstract

Photonic crystals are the dielectric material that the dielectric constant is varied periodically in space. As a result of the different extraordinary properties of the PhCs , the PhC based logic gates have number of advantages with respect to conventional logic gates,for example, fast speed, less power consumption, more throughput, compactness, high confinement.For the few frequency range, the light wave couldn't propagate through the PhCs, these frequency ranges is known as forbidden band gap and the flow of light can be controlled by engineering the photonic band gap.These logic structures are the fundamental part of optical system and optical communication system. These properties of PhCs make them as remarkable devices for realizing future optical computers. The main goal of this dissertation is to study the performance of 2-D PhC based all optical logic gate. For this reason Rsoft simulation tool is utilized which permits the design of different configurations of PhC structures. Firstly, a ultra precise and minimized all optical PhC OR logic gate has been acknowledged by the special combination of ring resonators,single line defect and MZI. We consider whole structure as a single cavity and the size of this structure is $12.6\mu m$ x $15\mu m$. It is completely closely packed and has the capacity of dense integration. Also, we used the basic structure of PhC ring resonator and designed optical NOT logic gate using Non-linear optical Kerr effect. Now, with the combination of these OR and NOT logic gates we designed optical NOR logic gate based on non-linear Kerr effect which consists of triangular lattice and the contrast ratio we obtained is more than 6dB. The main advantage of cascading of two optical gates is that the reflection losses should be reduced.

Contents

Chapter 1

Introduction

1.1 Introduction And Motivation

Recently, internet based communication has been widely used day by day. The need has overwhelmed the available bandwidths and higher speeds have become mandatory to satisfy the user demands and thus increasing the use of internet. Electronic devices and integrated circuits fulfills the increasing demand of high speed data transmission by innovations in microelectronics but due to various limitations such as expense of increased chip power consumption and dissipation. Therefore, a novel innovative solution to this problem is needed and photonic devices are one of the promising solutions in this horizon. So, ultra-fast speed computers and all-optical computing systems have considered copiously, since all of them have various advantages such as more throughput, less power consumption and fast speed [1]. As we know that the Optical logic gates are main components in communication systems and real time optical processing that perform various networking functions and many switching operations [2].Also, it is used to build optical computer which includes optical switches, optical interconnect and logic gates. For realizing these purposes various schemes have been illustrated, for example quantum dots [3], semiconductor optical amplifiers (SOAs) [4], multimode interference in SiGe/Si [5] and nonlinear SOI waveguide [6]. But due to some drawbacks for example, enormous size, hard to perform chip scale integration, more power utilization and less speed etc, they are less useful. The comparison between electronic logic gate and all optical logic gates are- logic levels,0 and 1 in binary logic are physically depicted by signal levels, may be voltage or

current in electronics circuits. In case of optical circuits, logic levels are represented by signal intensity/phase/polarization and are differentiated by a certain threshold. Photonic crystals (PhCs) are exceptional amongst the best choices for understanding these reasons [7]. PhCs are the dielectric materials that their RI (or equally dielectric constant) is periodic in one dimension (1D), two dimension (2D) or three dimension (3D) [8], [9].
So, in this dissertation introduction of 2D PhCs are explained in next chapter. So, in this research work all optical PhC based NOR logic gate are design by using 2D PhC. They have a bandgap that forbids propagation of the certain frequency range of light. This photonic bandgap structure manipulates beam of light just like semiconductor controls electric current and thus we get desired output wave. NOR gate is designed by the combination of logic OR gate and logic NOT gate which is designed in triangular lattice and thus we get the best results by this structure.

1.2 Objectives

- To design optical logic OR gate based on 2-D PhCs by peculiar combination of single line defect, ring cavities and MZI .
- To design optical logic NOT gate using Non- linear optical Kerr effect.
- To design all optical NOR gate by combining OR and NOT logic gate based on optical non-linear effect.

1.3 Thesis Organization

This thesis is organized in 7 chapters including this introduction.Chapter 1 gives the basic introduction of all optical logic gates(AOLG) and the increasing demand in the communication systems and real time optical processing .
Chapter 2 includes the introduction of photonic crystal and their types, types of defects in photonic crystal,their advantages and disadvantages and the literature survey regarding the topic of the dissertation. Literature review helps to perform this work easily. This chapter also includes the basic idea of non-linear effect

and non-linear optics which includes electro-optic Kerr effect and the non-linear optical Kerr effect. The non-linear Kerr effect which is used in designing various optical gates based on non-linearity such as all optical NOT gate.
Chapter 3 gives us the basic idea of research work done in past years.
Chapter 4 introduce the design of optical OR gate based on 2D PhC of silicon(Si) rods in the air background. It includes two line defects,MZI and the ring cavities through which the light wave travels and we get the desired output. The whole structure is designed on Rsoft simulation tool.
Chapter 5 presents the all optical NOT gate based on PhC of silicon rods in the air substrate. It consists of the ring resonator placed between upper and lower waveguide. This structure uses the non-linear Kerr effect to perform the operation of NOT gate. The whole structure is designed on Rsoft simulation tool.

Chapter 6 presents the design of optical NOR logic Gate which is designed using combination of optical logic NOT and OR gate. These structures consists of triangular lattice of silicon dielectric rods in air substrate.

Chapter 7 includes the conclusion and future prospect of the work.

Chapter 2

Photonic Crystal and Non-linear Effect

2.1 Photonic Crystal

A PhC is the dielectric material wherein the dielectric constant is periodically vary in space. The pattern by which the dielectric constant are arranged in space are known as crystal lattice and the space separating the two dielectric rods is known as lattice constant. When light propagate inside the crystal, then reflection and refraction occurs. It causes interference because of which few wavelengths close to periodicity of dielectric constant do not propagate through the PhC. The study of photonic crystal is practically equivalent to the semiconductor in solid state physics. And the flow of light is controlled by the photonic bandgap(PBG) [10]. So, we can change the flow of photons by engineering the structure for different applications. Photonic crystal forbids certain range of frequency just like semiconductor forbids certain energy. This forbidden range of frequency does not propagate through the lattice. The properties of PhC can be changed by the way toward doping in which the dielectric rods are added or removed in certain region. This addition or removal of dielectric rods are known as defect(point or line defect). This defect causes the localization of electromagnetic waves in the PBG. So, with the help of these defects the PhC can be used for different applications.

2.1.1 Types Of Photonic Crystals

PhCs can be categorized in the 3 ways on the basis of geometry: One dimensional (1-D), two dimensional (2-D) and three dimensional (3-D) PhC. The schematic diagram of PhC types are presented in fig 2.1

In 1-D photonic crystal structure, the dielectric material changes only in one di-

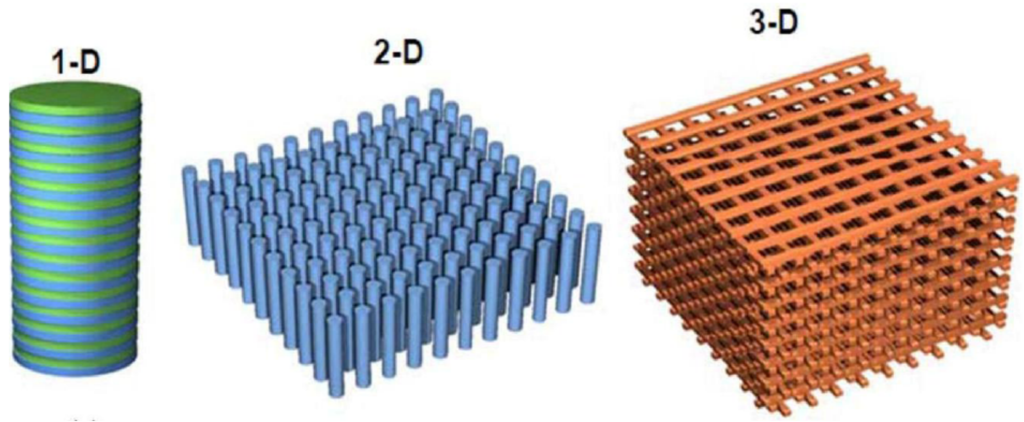

Figure 2.1: Types of PhC:(a) One dimensional(1D) (b) Two dimensional(2D) (c) Three dimensional(3D)

rection and the photonic band gap exists only in that direction. The propagation of EM waves is affected along that lattice direction where dielectric constant is changed.

In 2-D photonic crystal dielectric constant is periodically changed along two directions but it is uniform in third direction [11]. It is formed by placing periodically dielectric rods in the air background or by air rods in the dielectric substrate. The PBG exists in the plane of periodicity and the light do not propagate in this plane. For the propagation of light in this plane , the harmonic modes can be partitioned into two independent polarizations (TE and TM modes). Each polarization has its own different band structure [1]. It is possible that PBG may exist for only one polarization and not for other. Light can be localized in band gap or crystal by creating the defects.

In 3-D PhC, the dielectric constant is periodically changed in all directions. So , in 3-D structure there is no axis along which light can propagate in the structure which results in a complete band gap. It is difficult to localize the EM waves at the point defects and propagate through the linear defect. 1-D and 2-D PhCs has the ability to localize light at the point or line defect but the 3-D photonic crystal has the ability to localize the light in all directions.

Because of the simplicity and easy to fabricate characteristic of the 2D PhCs many researchers and scientists are attracted towards it. In this thesis work, 2D PhC with hexagonal lattice is considered.

2.1.2 Historical perspective of photonic crystal

In 1887, Lord Rayleigh studied the 1-D photonic crystals which consists of multi-layer dielectric stacks [12]. This investigation demonstrated the photonic band gap which otherwise called stop band. Vladimir P. Bykov examined the impact of band gap on the spontaneous emission inside the structure [13]. He also gave theoretical concept for 2-D and 3-D PhC structures. In 1979, Ohtaka developed a formal for the calculation of band gap of 3-D PhC structures [14].
In 1987, the two achievement papers were distributed by Yablonovitch and John. The main idea of Yablonovitchs paper was to control the spontaneous emission by engineering the density of states [15]. The idea of John's paper was to control the movement of light by utilizing PhC. [10]. It is difficult to design the structure in optical scale. It results most of work that were theoretically studied in 1991, Yablonovitch presented the first 3-D band gap in microwave regime [16].
Thomas Krauss demonstrated the 2D PhC at the optical wavelength in 1996 [17]. There are number of research work occurred around the world to improve the optical processing as well as to use the PhC slab. In 1998, Philip Russell developed first commercial used photonic crystal fiber [18]. The study of 2-D PhC is fast in comparison to 3-D, due to difficulty level of construction. There is study of naturally occurring PhC based structure for better understanding [19]. Below 2.1 shows the progress of photonic crystal in brief.

1887	Study of 1-D PhC which show the stop band [12]
1987	Two milestone paper was published based on 2-D photonic crystal [15], [10]
1991	Yablonovitch verified the existence for 3-D PhC in the micrometer range [16]
1996	Present the 2-D PhC at the optical wavelength [17]
1998	Development of first commercial optical fiber based on photonic crystal [18]

Table 2.1: Historical progress of PhC

2.1.3 Types of defects

There are two kinds of defects : point defects and line defects.

When a single lattice site is disturbed then a defect is created along a line in the z-direction. This defect disturbed the symmetry of periodic dielectric constant. It causes localization of light or a set of closely mode to a point in the plane of propagation [10], [15]. These modes have frequency within the band gap. This disturbance is known as point defect or cavity. In the simple words, cavity is surrounded by reflecting walls that dont allowed escaping of light thus leads to mode. There are number of ways like replace the single column from the crystal. The point defect in the PhC as shown in fig 2.2 below:

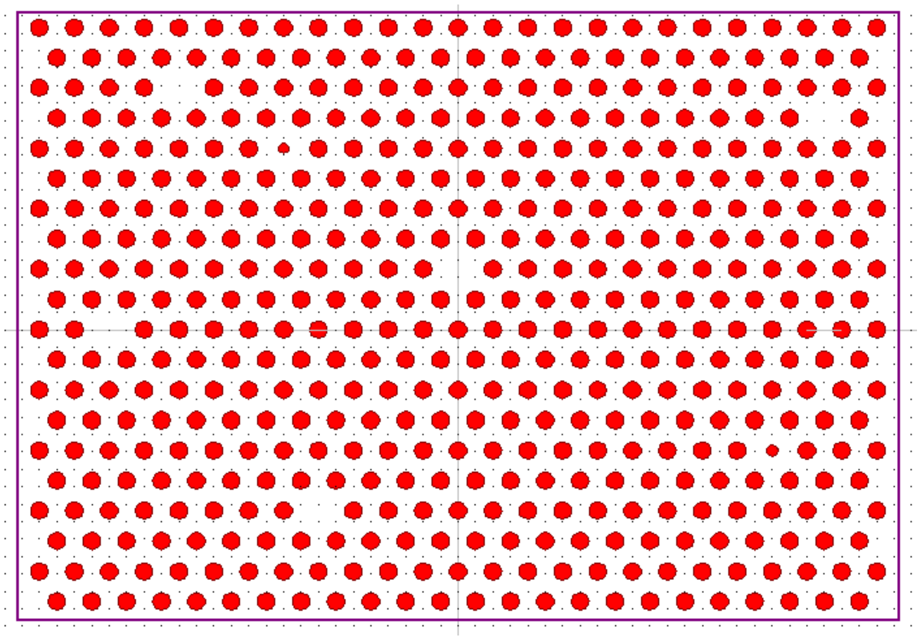

Figure 2.2: Different ways of introducing point defect in the structure(designed in Rsoft tool)

Another defect is the linear defects which is used to guide the light from point to another. The main idea is to form a waveguide from the photonic crystal by changing a linear series of crystal as shown in fig 2.3. Light with the frequency in the PBG that propagate in the waveguide is limited to the imperfection and can be coordinated along the defect. The mechanism of guiding light is index guiding i.e. TIR (total internal reflection) in the conventional dielectric waveguides but this mechanism confine the line only in the region of higher dielectric constant. In this case the mechanism of guidance is photonic band gap which is independent of the materials properties that filled in the core. This property is important for various applications in which reduction of interaction between the dielectric material and light is required.The fig 2.3 shows the line defect in the PhC.

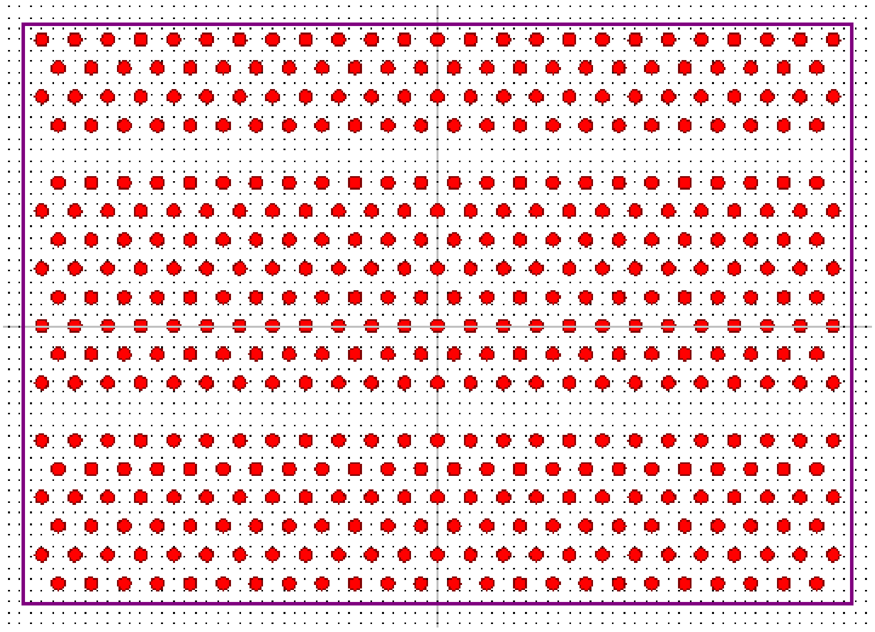

Figure 2.3: Different ways of introducing line defect in the structure(designed in Rsoft tool)

2.1.4 Advantages of photonic crystal

There are many advantages over the conventional optical devices. Its main advantage is to control optical properties and confinement of light by engineering the design of structure. Some of advantages are shown below :

- Photonic crystals reflect light of particular wavelength range which results in one mode of cavities unlike the metal cavities. The metal reflects all wavelength which results in infinite mode.
- The size of PhC devices are in the order of wavelength of light. Thats why the devices are compact in size.
- It can withstand with high electric fields.
- It processes the data at high speed as the travelling speed in structure is speed of light.

- Power consumption is low due to linear property of photonic crystal.
- It confines the light highly in the structure due to large difference present for effective index.
- It controls the spontaneous emission in the lattice.

2.1.5 Disdvantages of photonic crystal

Photonic crystal offers various disadvantages. The main disadvantage is complexity to design on the 3-D scale. The other disadvantage of photonic crystal is the designing cost. It is more expensive than the conventional devices.

2.2 Non-Linear Effect

2.2.1 Non-linear Optics

Non-linear optics is that part of optics which studies the behaviour of light in non-linear media where P and ϵ have a non- linear relation. It is responsible for a number of interesting and exotic phenomena such as: creating new frequencies, change the frequency of a light beam, changing its shape in space and time, mixing different laser pulses etc. Non- linear optical phenomena require very high intensities and electric fields. The comparison between linear optics and non-linear optics is that, In linear optics, the optical properties of materials are not dependent on intensity while in non-linear optics optical properties of materials are dependent on intensity. In non-linear optics, superposition principle is not applied. In linear optics, the frequency of light experiencing a medium is not change whereas it may change in non-linear optics. The linear and non-linear is presented in fig 2.4

In linear, $P = \epsilon\chi^1 E$
In Non-linear, $P = \epsilon\chi^1 E + \epsilon\chi^2 E^2 + \epsilon\chi^3 E^3 ....$
where,
E= Electric Field

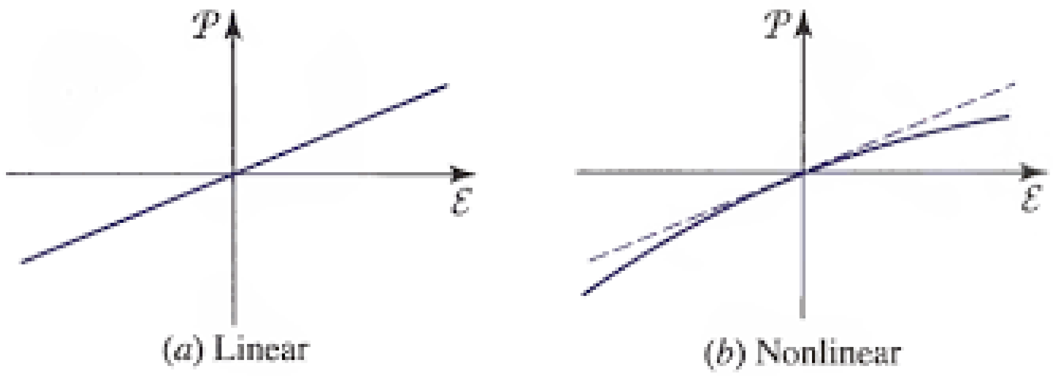

Figure 2.4: Linear and Non-linear

ϵ = vacuum permittivity

χ = susceptibility

There are two major effects are there in the non-linear optics one is the chi 2 effect and another is chi 3 effect. When only E square term is present and no other terms are there then the effect is called chi 2 effect. When the polarization is related to E as well as E square then we have chi 2 effect. When the polarization is related to E as well as E cube and the chi 3 term is there so, the phenomena related to that is called the chi 3 effect.

In chi 2 effect we have four different phenomena like Electro-optic effect, Sum and difference frequency generation,Second Harmonic Generation(SHG), Optical Parametric Amplification(OPA).

In chi 3 effect we have different phenomena such as Optical Kerr effect, third harmonic generation, self phase modulation(SPM) and cross phase modulation(XPM), four wave mixing etc.

Here are two different kinds of Kerr effects: electro-optic Kerr effect and optical Kerr effect. The working principle of both the types is depicted below:

2.2.2 Electro-optic Kerr effect

In this Kerr effect, a changing DC electric field is introduced to the non-linear optic medium, which results in the disturbance in the RI of the material. Consequently, the material is acting like a waveplate which polarize the light in a expected direction.

2.2.3 Optical Kerr Effect

Optical Kerr Effect is a self-induced effect in which the incident light produces an electric field. If I launch the electric field into the material then the material will behave in a non-linear fashion but there will be no change of RI ,then the effect is termed as chi 2 effect [20].The optical Kerr effect is very important in liquids. When an electric field is introduced on a Kerr media (mostly liquids), the liquid molecules started align themselves along the electric field. As a result, a change in the RI of the medium and the material turns into birefringent. Thus, incident light is modulated when it passes by a Kerr medium. The fig 2.5 shows the optical kerr effect.

$$n(E) = n - \frac{1}{2}\zeta^3 E \tag{2.1}$$

ζ is the Kerr coefficient or the quadratic electro-optic coefficient.

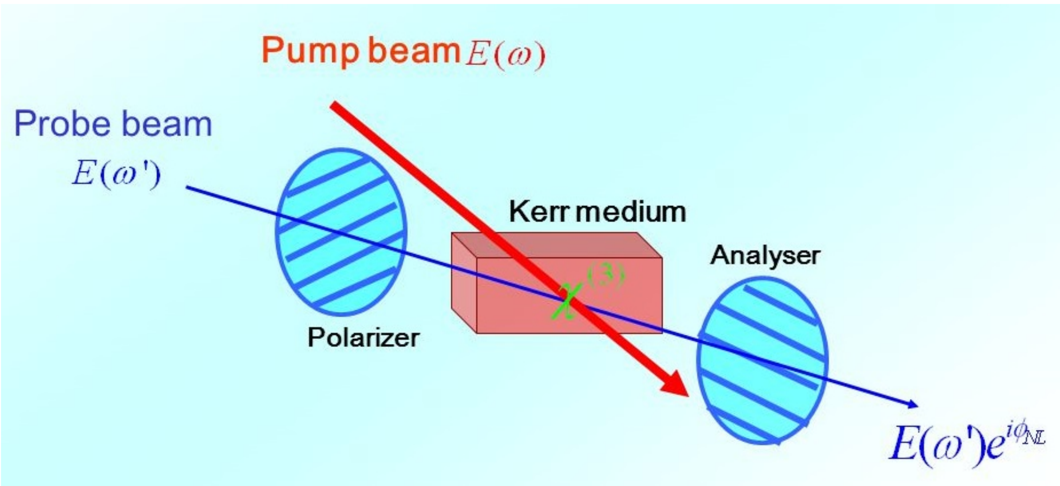

Figure 2.5: Optical Kerr Effect

2.3 Application

Here are some applications of Kerr effect mentioned below:

- Waveguides

- Spectroscopy of liquids
- Optical hetrodyne creation

Chapter 3

Literature Survey

Optical logic gate based on PhC has gained much interest in recent years. Nowadays, many researchers started to pay more attention to design PhC logic gates as it is one of main optical media to form optical processors and optical communication system.

Optical logic gates are generally divided into three categories based on designing and fabrications such as self-collimation, resonators and interference waveguide. Some authors designed logic gate based on the resonators. These resonators can be linear or nonlinear. Some authors studied optical gates based on interference waveguides. These structure are simple and easy. Some of the author investigated the self collimation phenomenon for the designing of logic gate. They also studied their advantages and disadvantages of each method.

The literature survey of all optical gates designed on PhC by various researchers in past years is shown below:

Mohammad Pirzadi, Ali Mir, and Dariush Bodaghi designed an optical logic OR gate on a 2D PhC [21]. This design of logic gate is a unique combination of MZI, ring resonators and line defects. He comes up with a novel, simple to manufacture and linear scheme for acknowledging precise logic OR gate. The size of OR gate structure is 12.5μm x 16μm. It is completely packed and has the capacity of dense integration.

Ashkan PASHAMEHR, Mahdi ZAVVARI and Hamed ALIPOUR-BANAEI utilized an essential structure of PhC ring resonator and designed optical logic gates which are operating by utilizing the Kerr effect [22]. The structure is designed for 1550 nm which is used as an telecom operation wavelength. The proposed gates consists of upper and lower waveguides in which light wave coupled through a resonator which is designed for dropping of special wavelength.

Junjie Bao et al. investigated a new idea for designing of all optical logic gates based on 2D PhCs in square lattice of Silicon rods in silica [23]. It comprises of two photonic crystal ring resonators(PCRRs) and cross shaped waveguide without using any optical amplifiers and non linear materials. The size of logic gate is very small as 6.8 μm only. The layout of optical logic gate are simulated and studied by PWE and FDTD method. The numerically demonstration of structure shows that these structure acts as logic NOR and NAND gate. The logic level high '1' and low '0' are defined. As this structure composed of linear material, it consumed low power as compared to the structure composed of non linear material.

Yi-Pin Yang et al. demonstrated a layout of all optical AND gate based on 2D PhC in triangular lattice [24]. It has two inputs and a single output. It composed of PCRR waveguide sandwiched between two input waveguides. The electric field distribution of the device is analyzed by FDTD method. The optical logic AND gate can function at different wavelength in the communication window of 1.3 μm and 1.55 μm due to the TIR and the interference in resonator. The definition of logic level high '1' and low '0' is considered to be more than 95% and less than 35% of transmission,respectively.

Yulan Fu et al. theoretically designed five types of logic gates in a 2D single PhC lattice simultaneously [25]. The five types of logic gates are NOT, OR, NAND, XOR, XNOR gates. The structure based on interference effect of light wave. This ingenious design consists of waveguide. By controlling the optical path difference, the different gates are possible to realize. These gates don't required high power for their logic function. This offers an effective and a simple approach for realizing integrated all-optical logic devices.

Raghda M.Younis et al. presented compact and linear designs of two optical AND and OR gates [26]. These devices consist of Y-shape line defect and ring cavities which are sandwiched between two linear waveguides. Transmission characteristics of designed optical logic gates are studied and simulated by FDTD method. The contrast ratio of designed logic AND gate is not less than 6dB. The transmission power for logic OR gate is not less than 0.5.The author calculated the fabrication tolerances of the designed devices found that the radius of rods of the ring cavities should be controlled with no more than ±3% and ±10% fabrication errors for optical AND gate and OR gates, respectively. In addition to this, the suggested design of AND and OR logic gates can operate at the bit rates of 0.208 and 0.5 Tb/s,respectively. Therefore, these devices can be used for future PIC due to their small size and simplicity.

P Andalib et al. designed closely packed all optical NOR gate based on nonlinear effect of PhCs [27]. It has two inputs and a single output. It consist of linear waveguides and PCRRs. The transmission characteristics of the design are analyzed and simulated by FDTD and PWE methods. Si rods with its appropriate properties are used as nonlinear material for the device. Si nano crystal rods are inserted in the ring resonators for nonlinear functioning of device. It localized the light beam because of resonance. The logic function of NOR gate is verified using simulation method. The fast speed of logic gate can perform with a bit rate of 138.9 Gb/s.

Chih Jung Wu et al. presented a design of compact optical NOT gate (OLNG) based on the waveguides of PhC without using any optical amplifier and nonlinear materials [28]. The numerically demonstration of the device through FDTD method shows that the layout acts as OLNG. It also presented a way to determine the operating parameters. The size of the optical logic NOT gate is 7a x 7a where 'a' is the lattice constant since no optical amplifier is required. It can operate at the low power as non linear material is not used. It has wide operating bandwidth. This is favorable for developing multi wavelength parallel processing optical logic systems and for large scale optical integration. This simple optical chip equals to ten thousands of conventional logic chips. It is used for future PIC as well as for developing all optical computers.

Chapter 4

Design of Optical Logic OR Gate based on 2D Photonic Crystal

Based on work presented in [21] a new design of all optical OR logic gates based on 2D PhC of silicon dielectric rods in the air substrate. The structure of OR Gate is efficiently acts as a logic switch and behaves as an OR gate. The continuous input wave is applied to the structure which is partially reflected and rest of the wave is transmitted to the output port through Mach-Zehnder interferometer and ring resonator. The structure has been simulated and analyzed by RSoft simulation tool. The size of this structure is 12.6μm x 15μm .

4.1 Introduction

All optical logic gates plays an prominent role in optical communication system since they are the basic elements for optical signal processing. There are various methods to design optical gates. Some of such methods are semiconductor optical amplifier (SOA) [29], optical waveguide interferometer [30], fiber grating [31], [32] but all have some drawbacks. So, the photonic crystal based logic gate are used because of various advantages like high speed , improved throughput, less power utilization and compactness. The flow of photon is control by the periodic change in the dielectric constant of photonic crystal. PBG represents the range of wavelength that propagate through the PhC utilizing plane wave expansion(PWE) method [33]. In this chapter, we comes up with the accurate and dense structure which is the special combination of line defect,ring resonators and MZI that is designed for realizing optical logic OR gate using 2D PhCs. In our structure logic level 1 and 0 are apart from each other and undesired port to port reflections are minimized. The various structure parameters for the design of all optical OR gate are presented in table4.1:

Parameters	**Material/ Values**
Wafer material	Air
Dielectric Rods	Si
Size of Structure	12.6μmx15μm
Refractive index of dielectric rods	3.43
Radius of rods	0.2a
Period	a
Lattice constant	0.5621075

Table 4.1: Structure parameters for the design of OR logic gate

4.2 Simulation Setup

Our OR gate structure consists of triangular lattice of silicon dielectric rods in air. lattice constant is the distance of separation between the two dielectric rods. It is represented by a. The radius of dielectric rods are selected to 0.2a and the RI of the rods is 3.43 which is placed in the air substrate having RI is 1. The MZI is sandwiched between the ring resonators followed by the line defects. The input ports are identify as M and N and the output port is identify as Q. This structure is completely symmetric about X-axis and transmission spectra is also symmetric about the X-axis. The two line defects having equal lengths and MZI's arms also have equal length. The structure is shown in fig 4.1

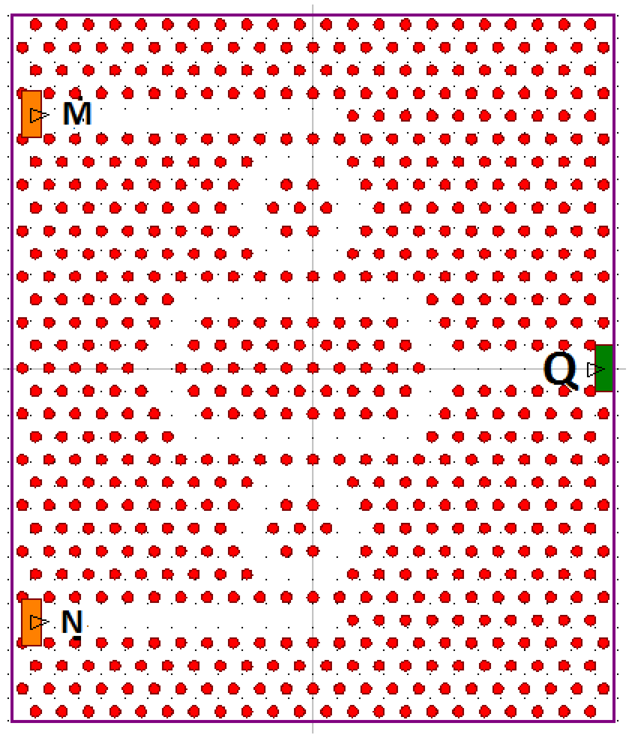

Figure 4.1: Layout of all optical OR Gate in Rsoft with inputs M and N and output Q

Logic OR gate is at logic level 0 when both the inputs M and N are logic 0 and when any one of the input or both the inputs are at logic 1 then output is at logic 1. This logic device is implemented using PhC in 2D triangular lattice. The block diagram of OR logic gate is depicted in fig 4.2

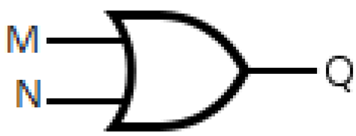

Figure 4.2: Block Diagram of OR Gate

4.3 Results and Discussion

The band diagram of this structure is calculated using plane wave expansion (PWE) method. The fig 3.3 gives the forbidden band gap. This band gap is equivalent to electronic band gap between conduction and valence band. The range of band gap is 0.27739 $\leq a/\lambda \leq$0.44815 for TE polarization mode where, λ is the free space wavelength. The light in this range cant propagate through this structure. The band gap is shown below in fig 4.3

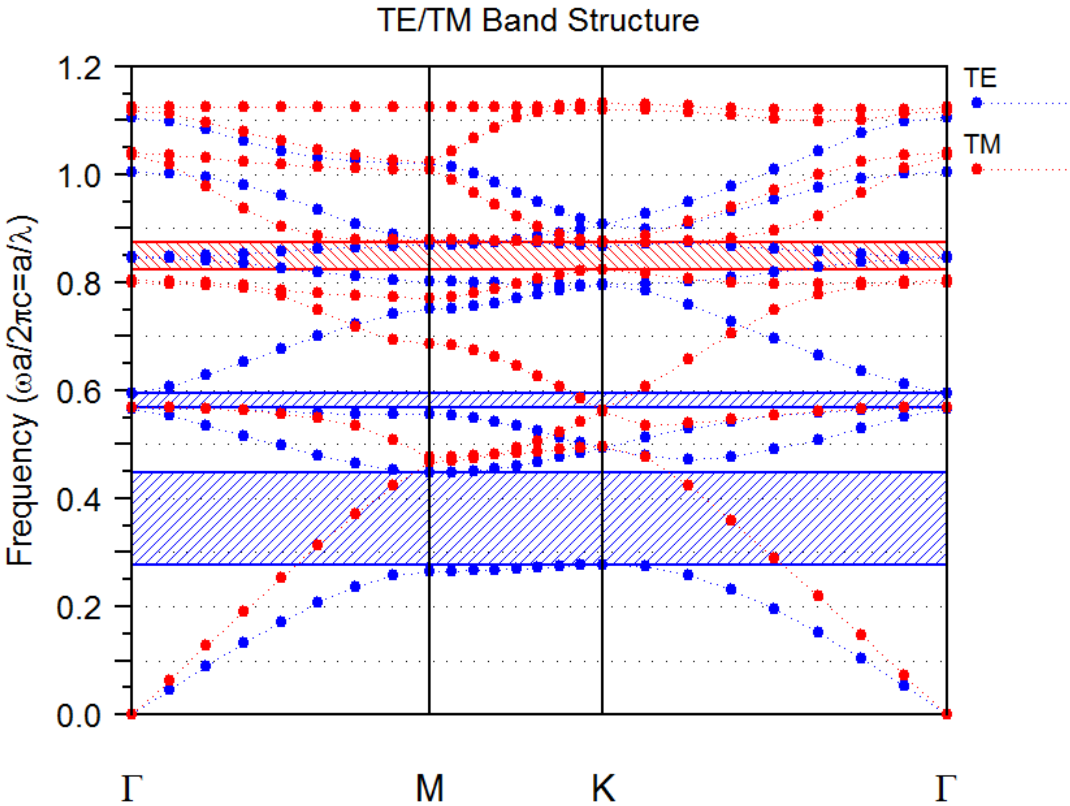

Figure 4.3: Band Diagram of OR logic gate

The display material profile shows the contour map of the index profile which shows the dielectric rods of Si in red colour whose refractive index is 3.43 which is surrounded by the air background of refractive index 1.The material profile of the structure is shown in fig4.4

A two dimensional optical logic OR gate is carried out using Rsoft simulation

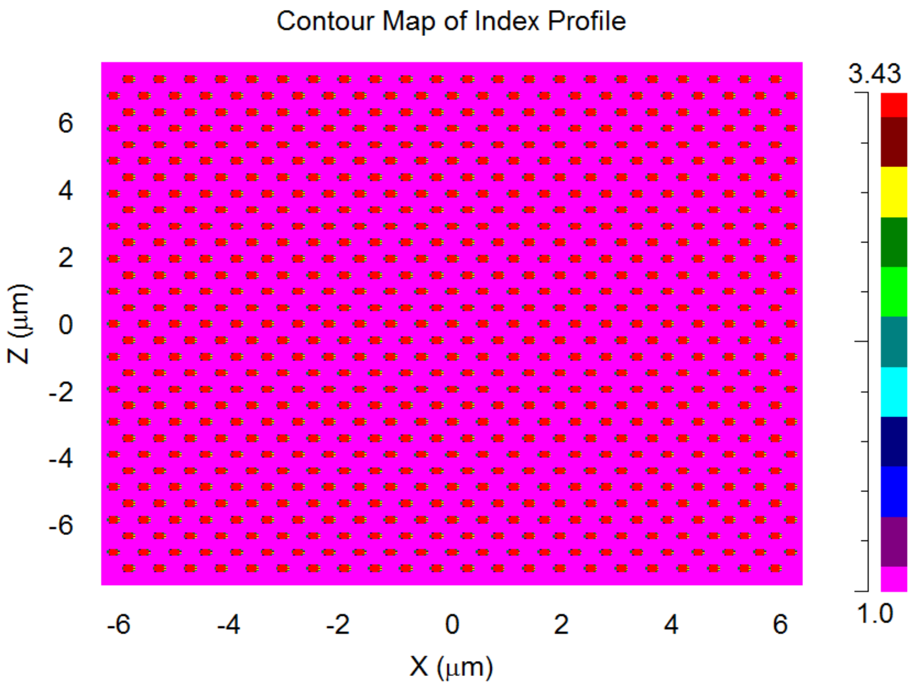

Figure 4.4: Material Profile of the structure

tool with transverse electric(TE) mode to obtain the logic function of logic OR gate.The input M and the input N have the launch field type is slab mode and both the inputs are launched with wavelength of 1.40526875μm. From the simulation results, the output at port Q follows the logic OR gate. The table with different combination of input and output is presented below in figure 4.2:

Input Port M	**Input Port N**	**Output Port Q**
0	0	0
0	1	1
1	0	1
1	1	1

Table 4.2: Truth table of OR logic Gate

The distribution of electric field through photonic crystal have been analyzed by Rsoft simulation tool. This describes the transmission path of light during different input conditions. When both of the inputs M and N are at low state ,then the output Q is also low otherwise output is high. This is shown in figure below:

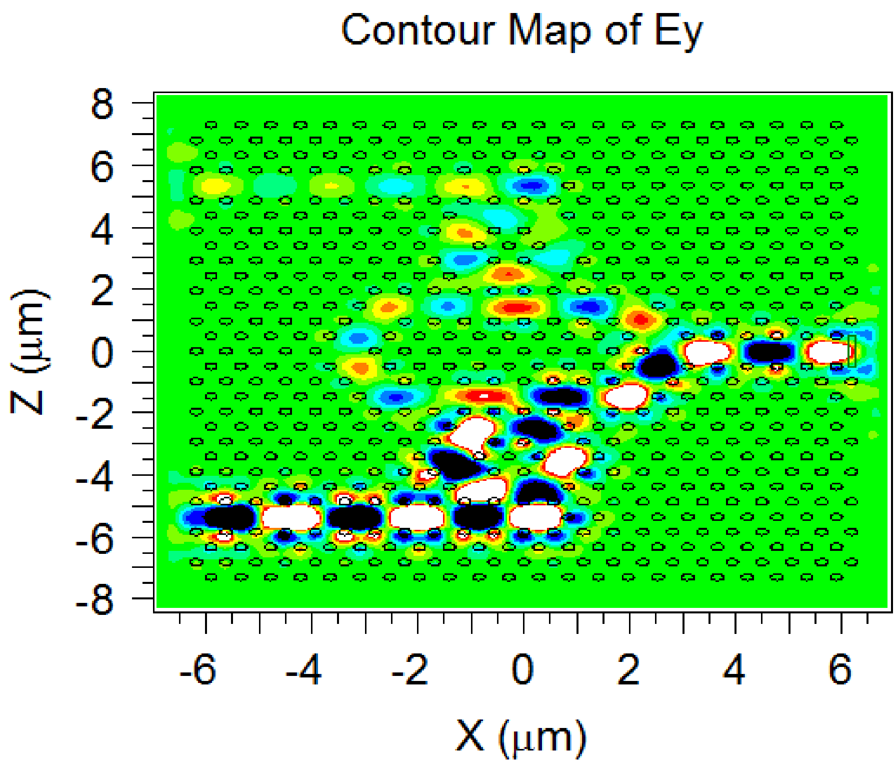

Figure 4.5: When input port M is ’0’ and N is ’1’ then output port Q is ’1’

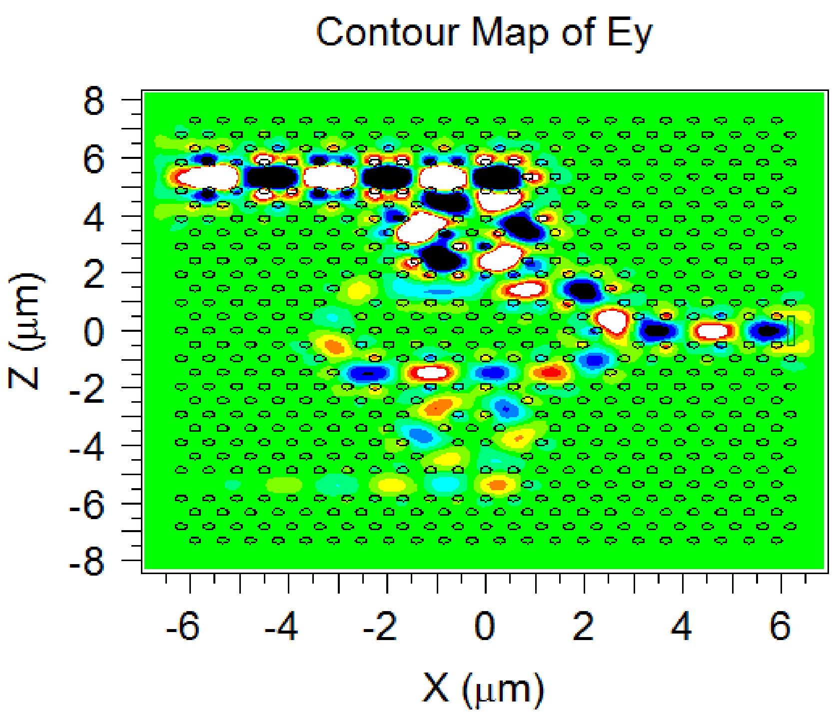

Figure 4.6: When input port M is ’1’ and N is ’0’ then output port Q is ’1’

In fig 4.5 we can see that the input port M=0 and N=1 so the continuous

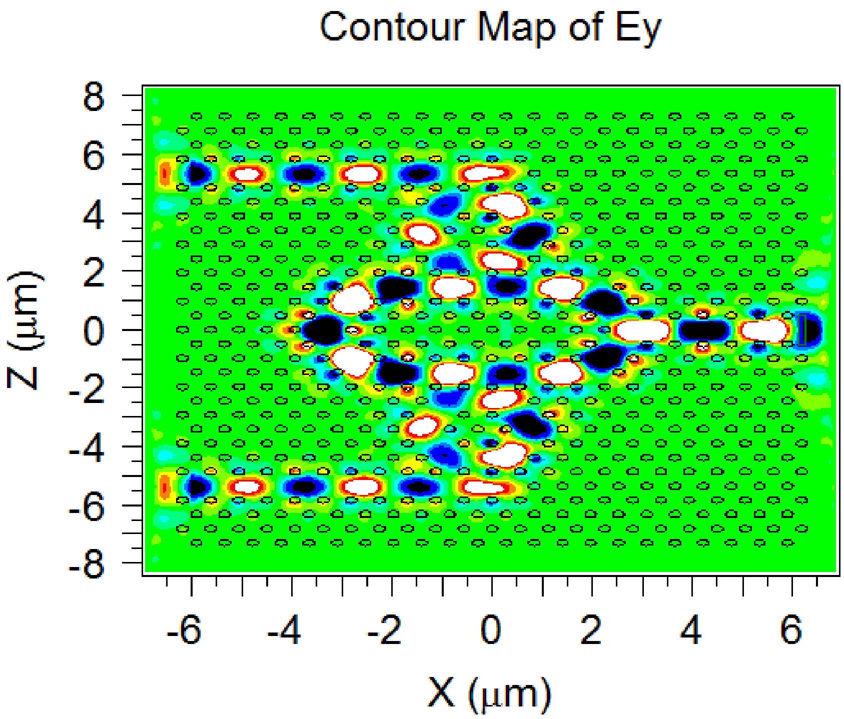

Figure 4.7: When input port M is '1' and N is '1' then output port Q is '1'

wave from port N is passing through the ring cavity and MZI and reaches to the output port Q and some of the light wave is coupled to the port M.

In fig 4.6 we can see that the input port M=1 and N=0 so the continuous wave from port M is passing through the ring cavity and MZI and reaches to the output port Q and some of the light wave is coupled to the port N.

In fig 4.7 we can see that the input port M=1 and N=1 so the continuous wave from both the ports is passing through the ring cavity and MZI and reaches to the output port Q.

So, in all the cases the output Q is at logic '1' when any one of the input is '1'. This structure acts as a logic OR Gate. The structure is designed in such a way so that we get the output as a OR gate.

4.4 Summary

We presented a new structure of all optical OR gates based on 2D PhC of silicon dielectric rods in the air substrate. The above photonic structure acts as a logic switch and behaves as a logic OR gate. This structure is simulated and analyzed by Rsoft simulation tool and PWE.The lattice constant "a" is calculated with the help of bandgap range 0.27739 $\leq$a/λ $\leq$ 0.44815 where λ is equal to 1550 nm.By putting the value of λ we calculate the lattice constant "a" value which is equivalent to 0.5621075. Thus,we put this "a" value in $0.2a$ to find out the radius of rods which is equal to 0.1124215.We set period equals to 0.5. The free space wavelength is equal to 2.5a and by putting the value of "a" in this expression we get the free space wavelength λ which is equivalent to 1.40526875. The continuous input wave is applied to the structure which is partially reflected and partially transmitted through the ring cavity and MZI. With the help of point defect and line defect the entire structure is designed. The main advantage of this photonic structure is that the size of the logic gate is small (about $15\mu m \times 12.6\mu m$) and it operate at 1.40526875 μm. Therefore, it can be used for various photonic integrated circuits. This structure demonstrates the likelihood of designing other logic functions. It very well may be utilized to structure different logic circuits such as flip flop, decoders etc.

Chapter 5

Designing of all optical NOT gate based on PhC ring resonator using non- linear Kerr Effect

For designing of all optical devices the PhC based ring resonators are regularly utilized. We use the basic structure of ring resonator to implement the NOT gate using non-linear Kerr effect. The proposed NOT gate structure comprises of two waveguides which are situated on the upper and lower side of the ring resonator. We utilize the numerical methods for performing the simulation and studied the optical properties of the structure,for example,plane wave expansion(PWE) and finite difference time domain(FDTD).

5.1 Introduction

Optical logic gates are widely used in photonic networks because of their properties which requires more data transfer capacity to route the fast speed optical signals. The all optical NOT gate is designed with the help of third order non-linear effect. The structure consists of the ring resonator followed by upper and lower waveguides in which the light wave passes through and reaches to the lower waveguide [34], [35], [36]. The refractive index can be changed with the help of thermo-optic, electro-optic , or optical Kerr effect. Among them, only Kerr effect is used for every single optical applications.The figure consists of the 4 ports in which the input light from port A is coupled to lower waveguide by the ring resonator and other input port is the reference or bias input. The simulation is performed by commercial software Rsoft.

In this chapter we propose and simulate the all optical NOT gate which is designed using two identical waveguides and a ring resonator which is used to couple the light to the lower waveguide. The structure uses the non-linear Kerr effect for the simulation. The various structure parameters for the design of optical NOT gate are presented in table 5.1:

Parameters	**Material/ Values**
Wafer material	Air
Dielectric Rods	Si
Size of Structure	$21\mu m$ x $27\mu m$
Refractive index of rods	3.46
Radius of rods	$0.124\mu m$
Period	0.5
Lattice constant	0.616
Operating wavelength	$1.55\mu m$

Table 5.1: Structure parameters for the design of NOT logic gate

5.2 Simulation Setup

Our NOT gate structure consists of triangular lattice of silicon rods in the air background. Lattice constant is the distance of separation between the two dielectric rods and it is represented by a which is 616 nm and the radius of the dielectric rods is 124 nm and the RI of dielectric rods is 3.46 which is placed in air substrate having RI is 1. The basic structure of NOT gate is $21\mu m$ x $27\mu m$ having hexagonal lattice structure of dielectric rods in air substrate. The kerr effect coefficient is 1.5×10^{-16}. The ring resonators is placed in the center of the two identical waveguide.

The layout of the NOT gate structure is depicted below in fig 5.1:

In the above structure of NOT gate, two inputs A and bias are shown while

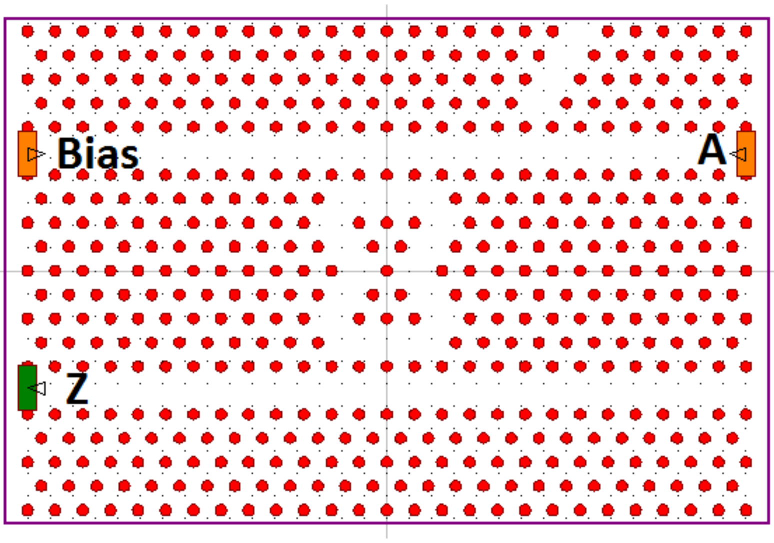

Figure 5.1: Layout of the proposed NOT Gate

Z is the output port from where we get the output of NOT gate. The bias is always high and used as a reference input port. When no optical field launched to input A, then the optical wave from the bias port reaches to the ring resonator and coupled to lower waveguide. Thus we get the high output at Z . When the optical field is launched to input A and we know that the bias is always in high state then both optical fields combine and a high intensity light passes to the ring resonator, thus the resonant wavelength changes. As a result, no light enters to lower waveguide and we get low output. This logic gate uses Kerr effect to perform its function. The block diagram of the NOT gate is presented below in fig 5.2

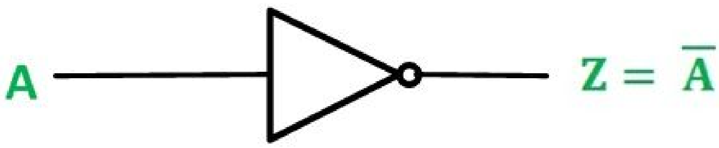

Figure 5.2: Block diagram of NOT Gate

5.3 Results and Discussion

The band diagram of this NOT gate structure is calculated using of plane wave expansion (PWE) method. The fig 5.3 gives the forbidden band gap. This band gap is equivalent to the electronic band gap between conduction and valence band.

The range of band gap is $0.28 \leq a/\lambda \leq 0.44$ for TE polarization mode, where, λ is the free space wavelength. The light in this range cant propagate through this structure. It is operated at $1.55\mu m$ which is fundamental third optical window.

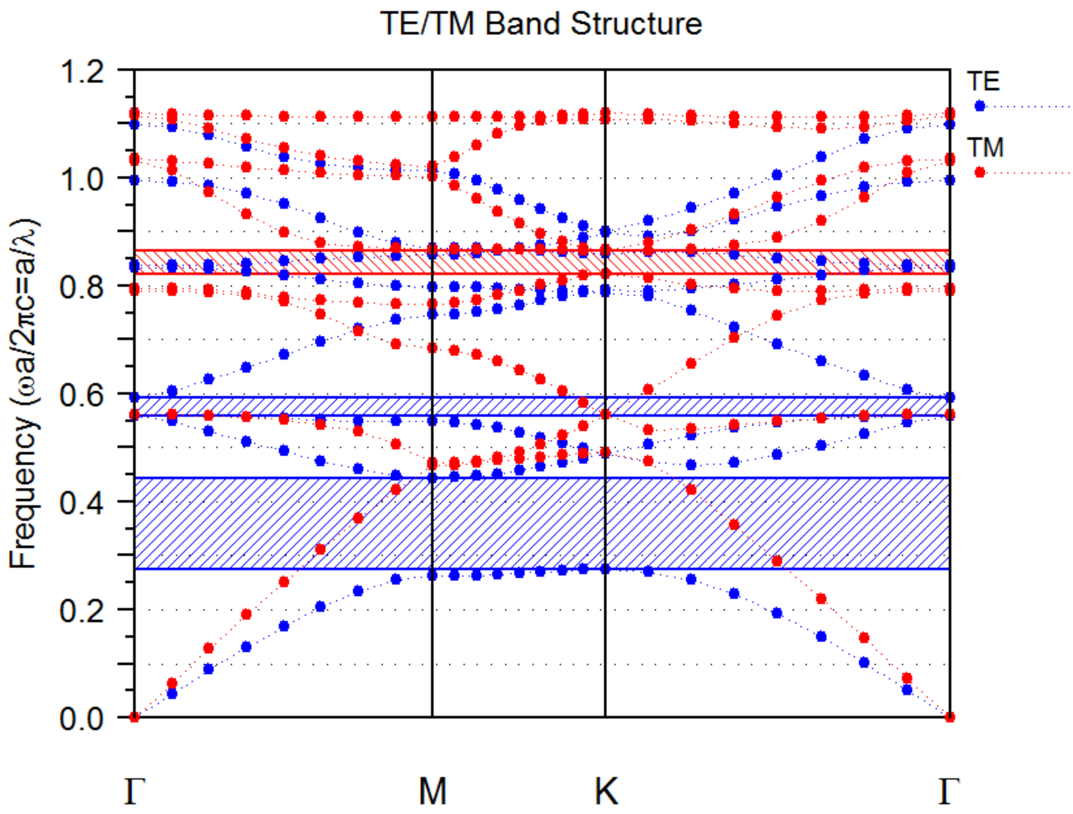

Figure 5.3: Band Gap of NOT Gate

The material profile shows the contour map of the index profile which shows the dielectric rods of Si in red colour whose RI (n) is 3.46 and it is surrounded by the air background of RI(n) is 1.The material profile of this structure is presented below in fig 5.4:

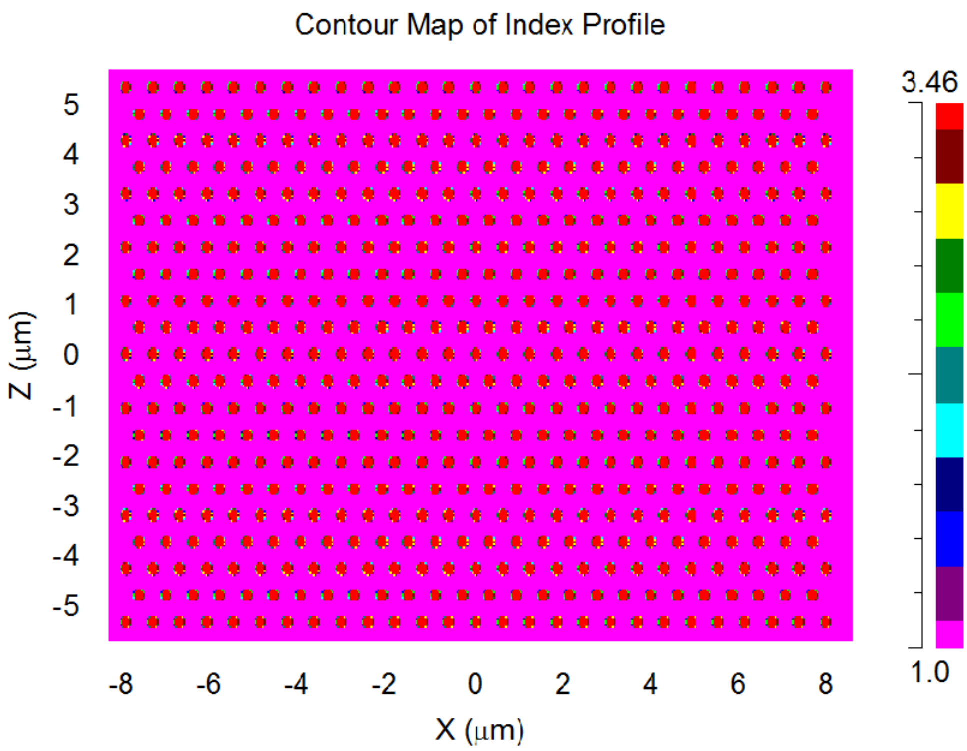

Figure 5.4: Material Profile of the structure

A two dimensional optical logic NOT gate is carried out using Rsoft simulation tool with transverse electric(TE) mode to obtain the logic function of logic NOT gate. A and Bias are the two input ports and Z is the output port of this structure. The input A and bias have the launch field type as gaussian mode and the inputs are launched with wavelength of $1.55\mu m$. From the simulation results, the output at port Z follows the logic NOT gate. The NOT gate uses the non-linear Kerr effect to get the desired output. The table with different combination of input and output is shown below in figure 5.2:

Input Port Bias	**Input Port A**	**Output Port Z**	**Observed output power P**
1	0	1	0.6
1	1	0	0.12

Table 5.2: Truth table of NOT Gate

The distribution of electric field through PhC have been analyzed by Rsoft simulation tool. This describes the transmission path of light during different input conditions. When the input A is at low state, then the output Z is in high state. When the input is in high state, then the output is at low state. This is shown below:

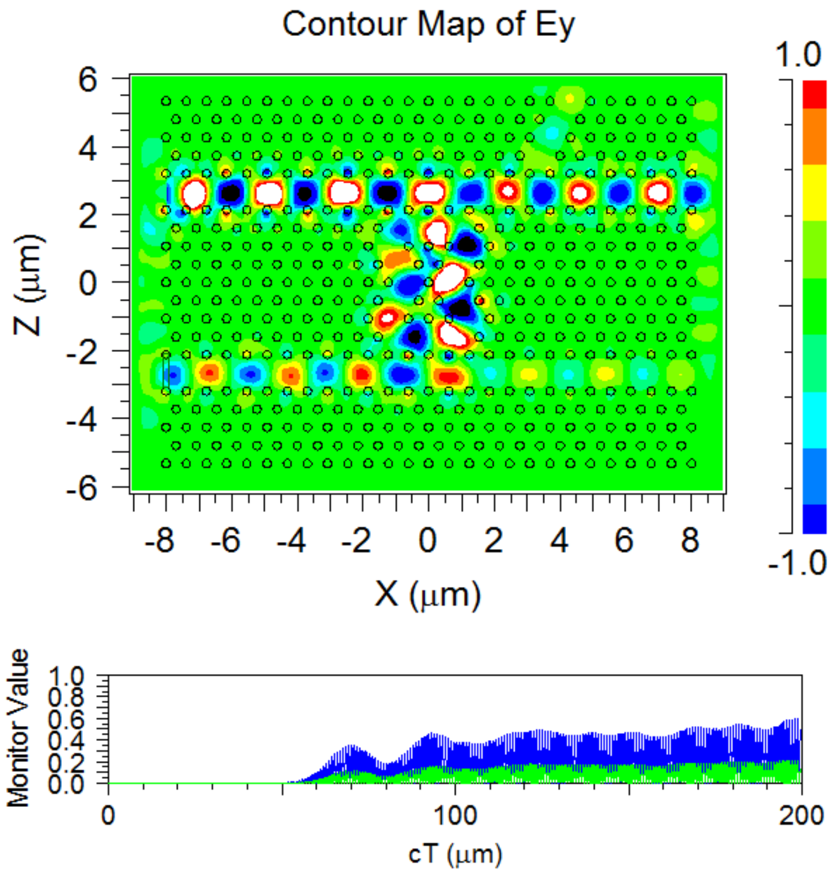

Figure 5.5: When A="0" then Z="1"

In fig 5.5 we can see that the input port A="0" then the optical wave from the bias port reaches to the ring resonator and coupled to the lower waveguide. Thus we get the high output Z="1"

Similarly, In fig 5.6 we see that the input port A="1" or the continuous high intensity wave is launched and the optical field of bias is also high then both optical fields combines and a high intensity light passes to the ring resonator and the resonant wavelength changes. Therefore, no light enters to lower waveguide and we get low output or Z="0". So, the structure behaves as an optical NOT gate. Here, from the results we obtained high contrast ratio of approximately

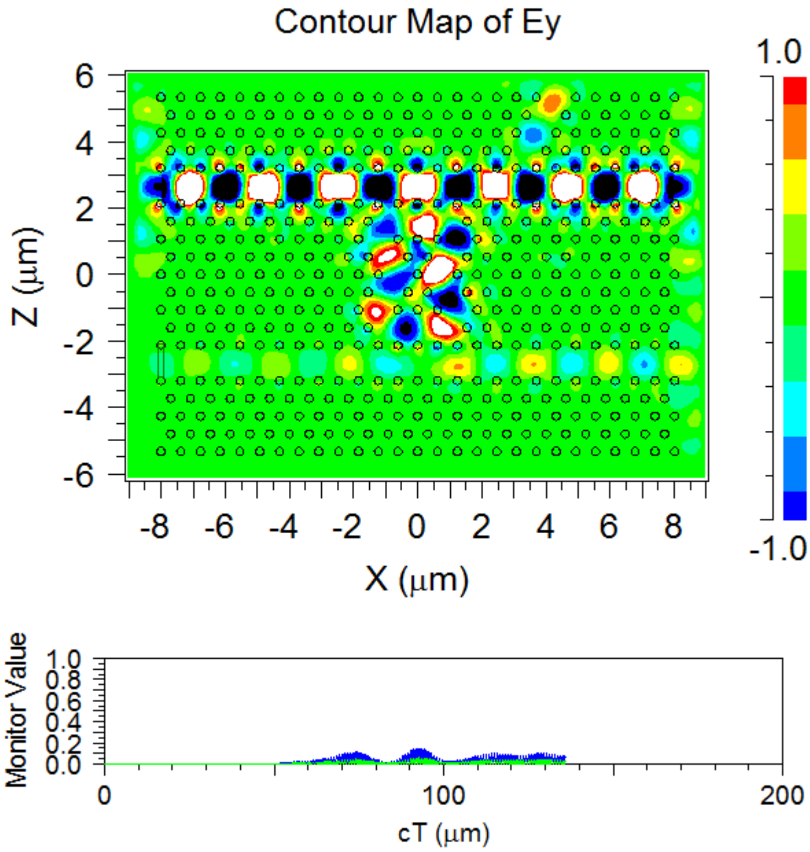

Figure 5.6: When A="1" then Z="0"

7dB.

$$ContrastRatio(dB) = 10\log\frac{P_{out1}}{P_{out0}} \tag{5.1}$$

$$ContrastRatio(dB) = 10\log\frac{0.6}{0.12} = 6.9dB \tag{5.2}$$

5.4 Summary

In this structure, using a ring resonator and the two identical waveguide, we design a photonic NOT gate using non-linear Kerr effect. When two input optical fields simultaneously enter into the ring resonator then Kerr effect occurs in which the high intensity optical field increases and then the RI changes which results in the shifting of resonant wavelength. For this, a bias or reference input is used which has a wavelength equals to resonance λ of the ring. We get the good contrast ratio here .Thus, we obtained the NOT Gate operation.

Chapter 6

Designing of Optical NOR Logic Gate by combining optical OR and NOT gates using non-linear kerr effect on 2D PhC

An optical NOR gate is designed using optical OR and NOT logic gate by cross connection of both gates without using other external devices. The design of logic NOT and OR gate are separately simulated and analyzed with the help of Rsoft simulation tool. The layout of NOR gate is designed in Rsoft. The operation is based on non-linear Kerr effect.

6.1 Introduction

Due to the demand of increasing high capacity the data is transmitted in digital format. Due to the various limitations of electronics devices, these devices do not fulfill the high speed demand [36] [37] [38]. So, there is a need of all optical devices which fulfill all the needs such as high speed and miniature size. Optical gates are designed in various different ways. Some are based on non-linear effects in , in semiconductors [39], waveguides [40] and in optical fiber [41].For cascading of two logic gates various reflection losses should be reduced. Optical Kerr effect is used to design a NOR Gate. The value of the Kerr effect coefficient is 1.5×10^{-16}. Photonic crystal(PhCs) are best to design logic gates and analyze their functions. PhCs based logic gate has special properties such as compactness, less power utilization, fast speed etc. The light propagate in the structure and some of light reflects at each interface of the dielectric material which results in interference because of which few wavelengths are not propagate in the PhC. A Photonic bandgap crystal(PBG) is that structure which can manipulate light wave just like semiconductor controls electric current.

This chapter presents another methodology for designing a logic NOR gate by combining NOT and OR logic gate. By using this methodology reflection losses are minimized at input ports and thus we get high contrast ratio. Contrast Ratio is the ratio of the power of logic "1" to logic "0". The structure parameter for designing NOR logic gate using PhC are shown in table 6.1:

Parameters	**Material/ Values**
Wafer material	Air
Dielectric Rods	Si
Size of Structure	$50\mu m$ x $31\mu m$
Refractive index of rods	3.46
Radius of rods	$0.1124215\mu m$
Period	a
Lattice constant(a)	0.5621075
Operating wavelength	$2.5 * a$

Table 6.1: Structure parameters for designing of optical NOR gate

6.2 Simulation Setup

6.2.1 Layout of logic OR and logic NOT gate

The structure of optical OR and NOT gate are individually designed. Our OR gate structure consists of triangular lattice of silicon rods in the air background. Lattice constant is the distance of separation between the two dielectric rods. It is represented by a. The radius of dielectric rods is 0.2a and the RI of the rods is 3.43 which is placed in the air substrate of refractive index 1. OR gate is designed by the special combination of ring cavities, MZI and two waveguides. The MZI is sandwiched between the ring resonators followed by the line defects. The size of the OR gate is 12.6μm X 15μm and the lattice constant is about 0.5621075.

NOT gate structure consists of triangular lattice of silicon rods in air background. Lattice constant is the distance of separation between the two dielectric rods and it is represented by a which is 616nm and the radius of the dielectric rods is 124 nm and the RI of dielectric silicon rods is 3.46 which is placed in air substrate having RI is 1. The basic structure of NOT gate is 21μm x 27μm having hexagonal lattice structure of dielectric rods in air substrate. The Kerr effect coefficient is 1.5×10^{-16}. The ring resonators is placed in the center of the two identical waveguide. The operating wavelength λ=1550 nm and the band diagram of both the structures is calculated using plane wave expansion (PWE) method. These are the individual structures of the logic OR and NOT gate. By combining these two structures we design NOR logic gate.

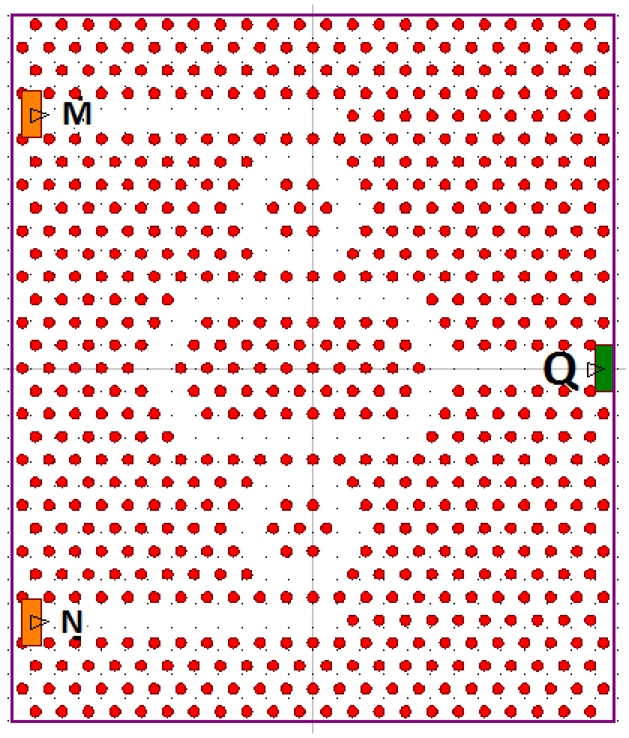

Figure 6.1: Layout of optical OR Gate in Rsoft with inputs M and N and output Q

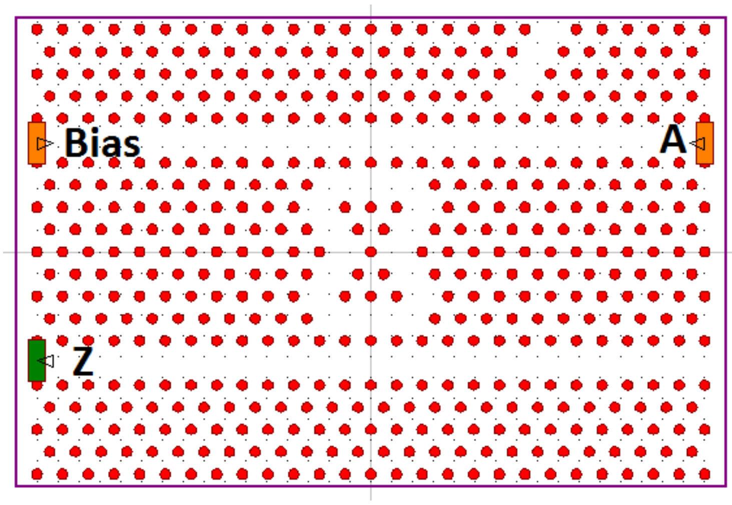

Figure 6.2: Layout of the proposed NOT Gate

6.2.2 Layout of NOR logic gate using OR and NOT gates

The complement of OR logic gate is logic NOR gate. NOR gate is designed by combining OR and NOT gate without utilizing external devices such as coupler, amplifier etc. It is designed using triangular lattice PhC with structure size of $50\mu m$ x $31\mu m$. The dielectric rods are of Si and the substrate is air. The lattice constant of dielectric rods is 0.5621075 and the radius is equal to $a \times 0.2$ which is equal to 0.1124215 and the period is equal to lattice constant. The operating λ is $2.5 \times a$ which is equal to 1.40526875. The layout of optical NOR gate is presented in fig 6.3:

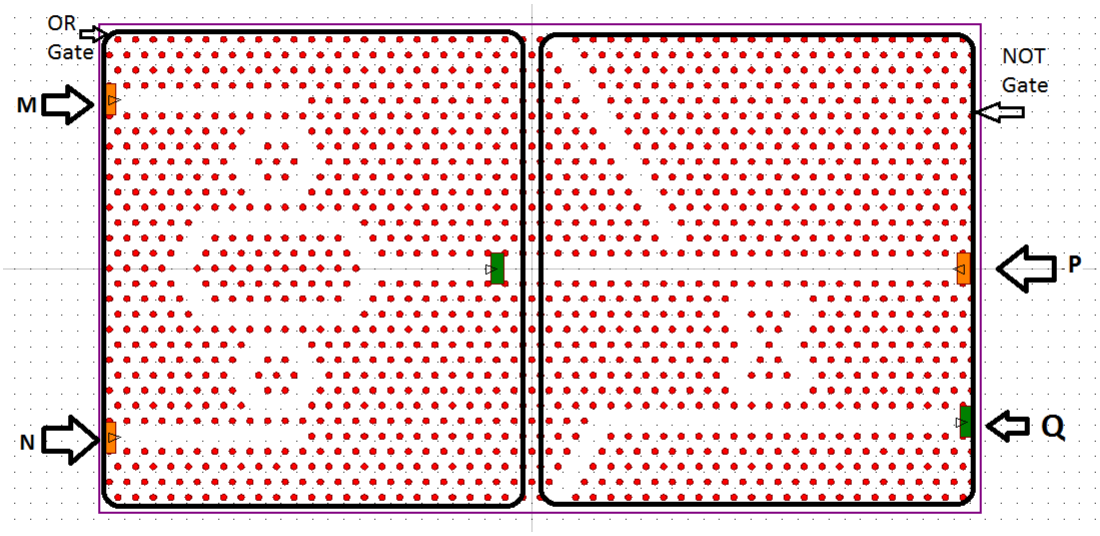

Figure 6.3: Layout of the NOR logic Gate

The NOR gate is the universal logic gate which is used to make any other logic gate. The NOR gate operation is obtained by the complement of logic OR gate. When both the inputs are low or "0" then only it gives high output or logic "1" otherwise it gives low output. The block diagram of NOR gate is presented in fig 6.4:

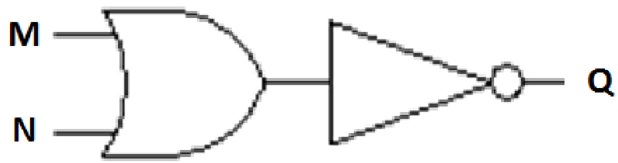

Figure 6.4: Block diagram of NOR Gate

6.3 Results and Discussion

The band diagram of the structure is calculated using of plane wave expansion (PWE) method or BandSOLVE. The band gap is equivalent to the electronic band gap between conduction and valence band. The range of band gap is 0.27711

$\leq$a/λ $\leq$ 0.44819 for TE polarization mode where λ is the free space wavelength which is equal to 2.5 $\times$ a .The light in this range cant propagate through this structure. It operates at 1.40526875 μm which is obtained by free space wavelength formula. The band gap of NOR logic gate is presented in fig 6.5:

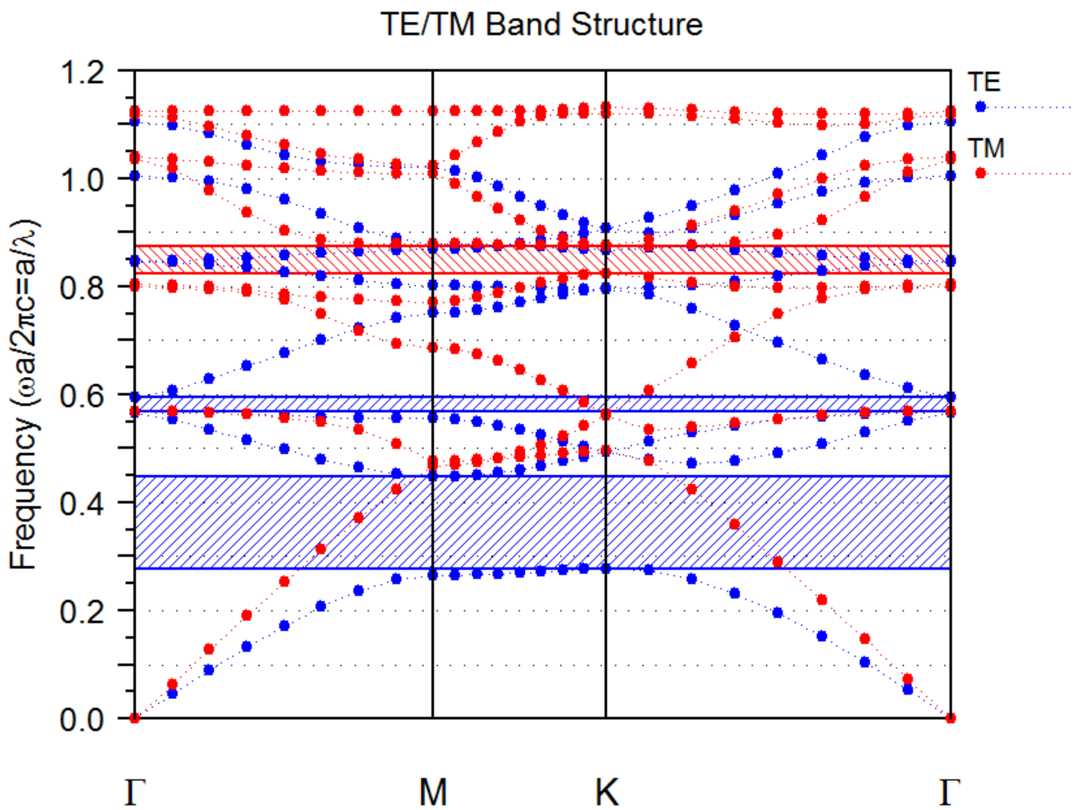

Figure 6.5: Band Diagram of NOR logic gate

A two dimensional logic NOR Gate is designed in Rsoft simulation tool. The structure has three inputs M,N and P and P is the bias input which is used as a reference input i.e always high and Q is the output of NOR gate. The truth table of NOR gate is mentioned in below table 6.2: The propogation of light

Input Port M	Input Port N	Bias Port P	Output Port Q
0	0	1	1
0	1	1	0
1	0	1	0
1	1	1	0

Table 6.2: Truth table of optical NOR Gate

wave in the given layout structure is similar to that of NOR logic Gate or we can say the structure behaves as an NOR gate. All the combinations of the inputs through which the light wave launched as a Continuous wave with their outputs are shown below:

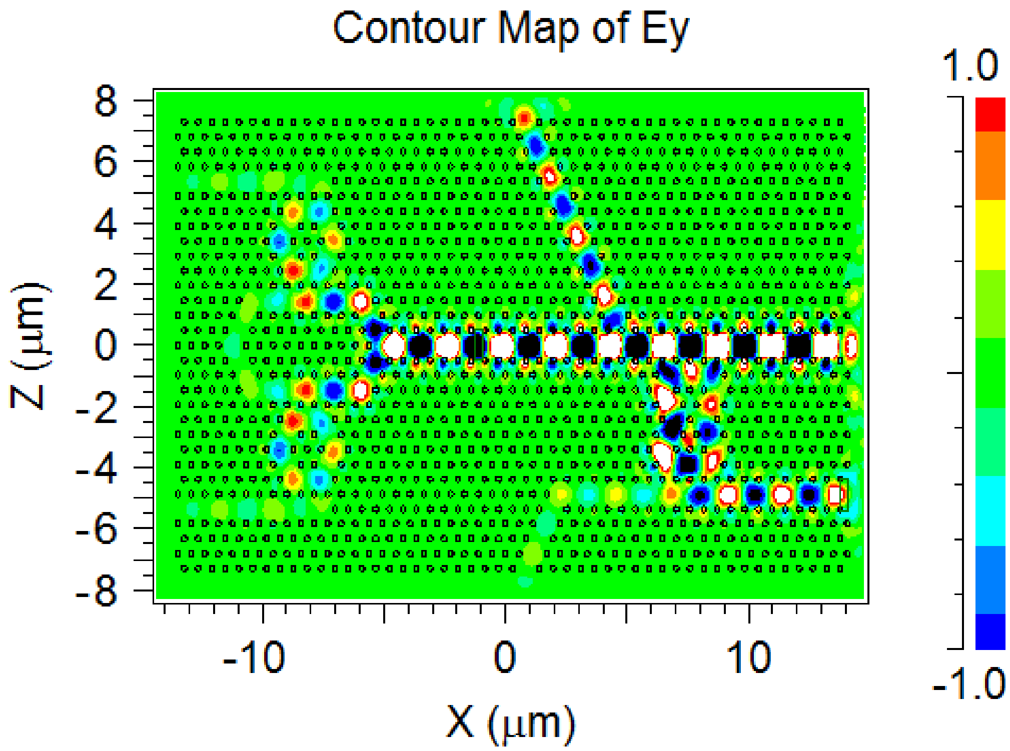

Figure 6.6: When M="0" , N="0" then Q="1"

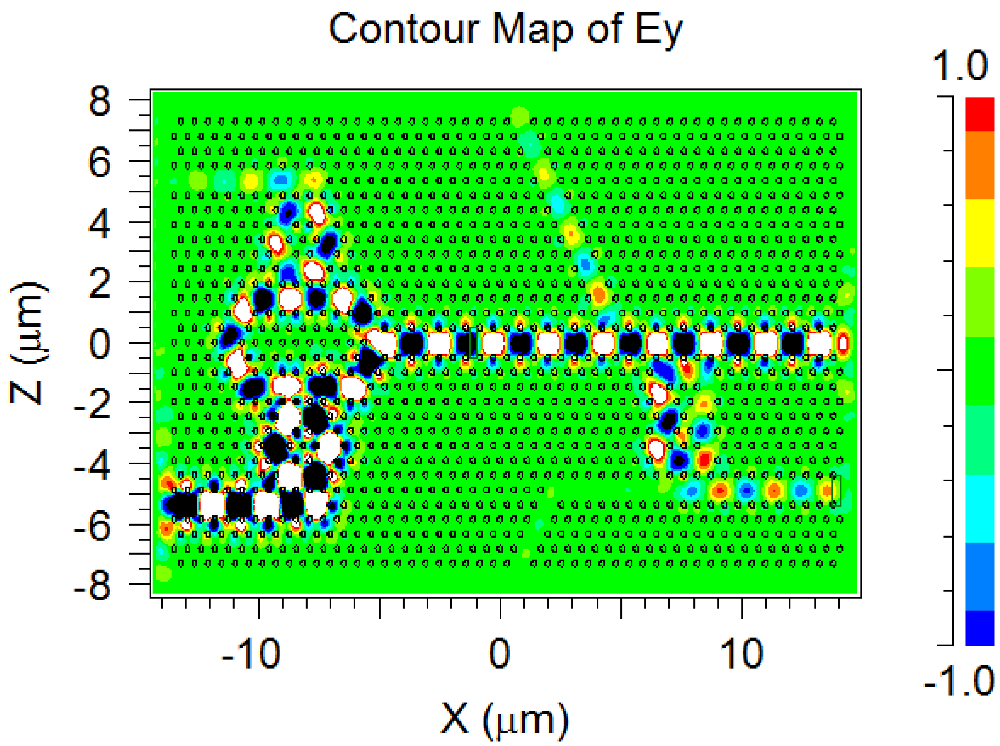

Figure 6.7: When M="0" , N="1" then Q="0"

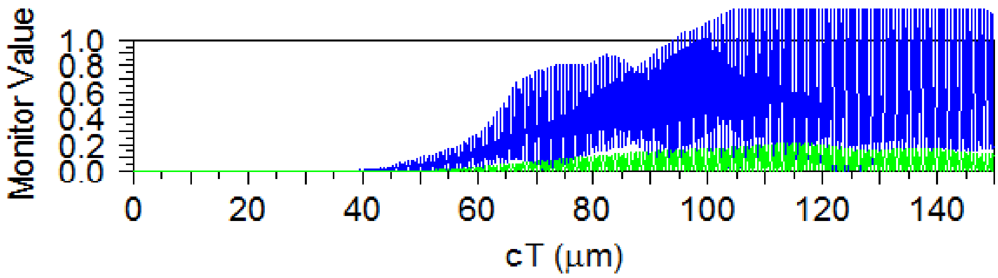

Figure 6.8: Monitor Value when M="0" , N="1" then Q="0"

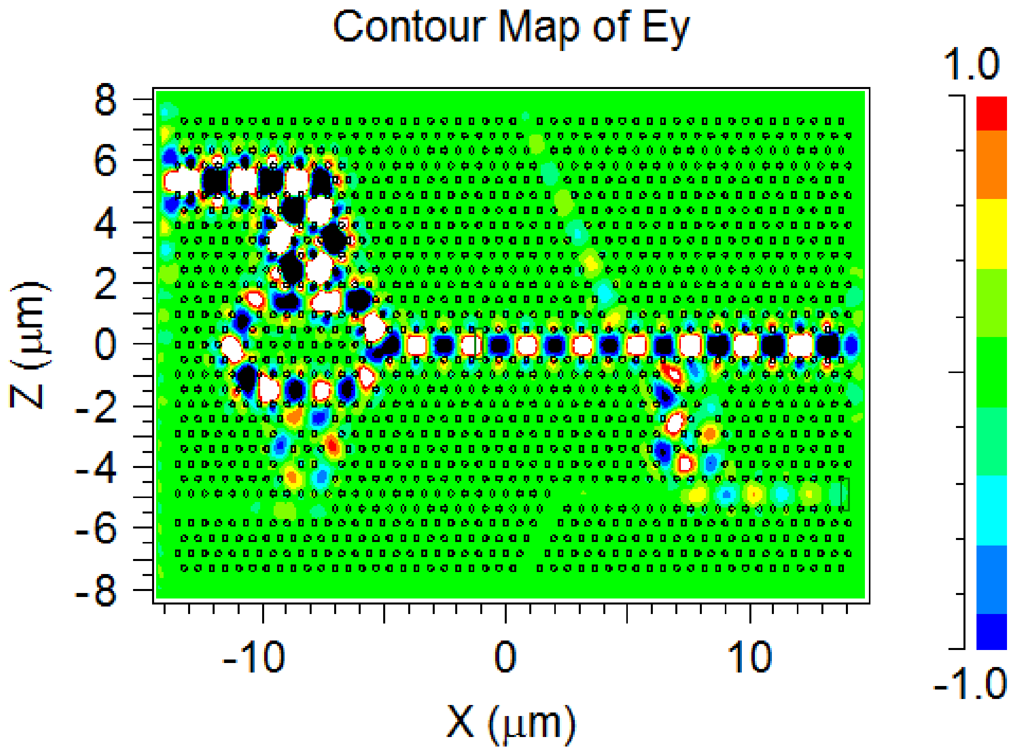

Figure 6.9: When M="1" , N="0" then Q="0"

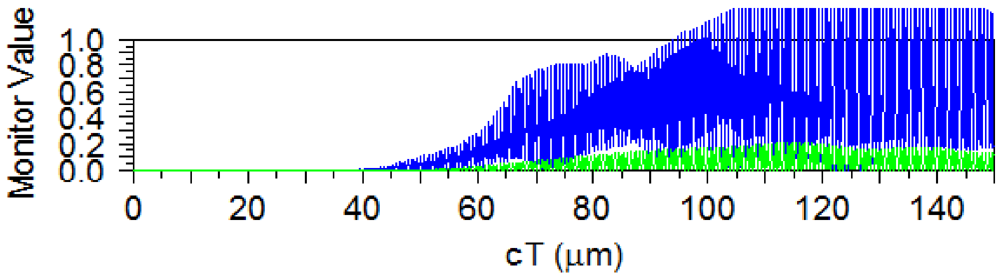

Figure 6.10: Monitor Value when M="1" , N="0" then Q="0"

As we saw in the above figures, the monitor values shows the power of the output port. When input M is "0" or "1" and N is "1" or "0" then we obtained low power at the output port or we can see from the monitor value that the output power is very negligible i.e. 0.25 approximately. When both inputs are at logic "1" then also we get low output i.e. 0.25 approximately.When inputs M and N are low or logic "0" then we get the high output power. In this case the power from the bias or reference input goes down by the ring resonator and reaches to the output port Q thus we get maximum output.

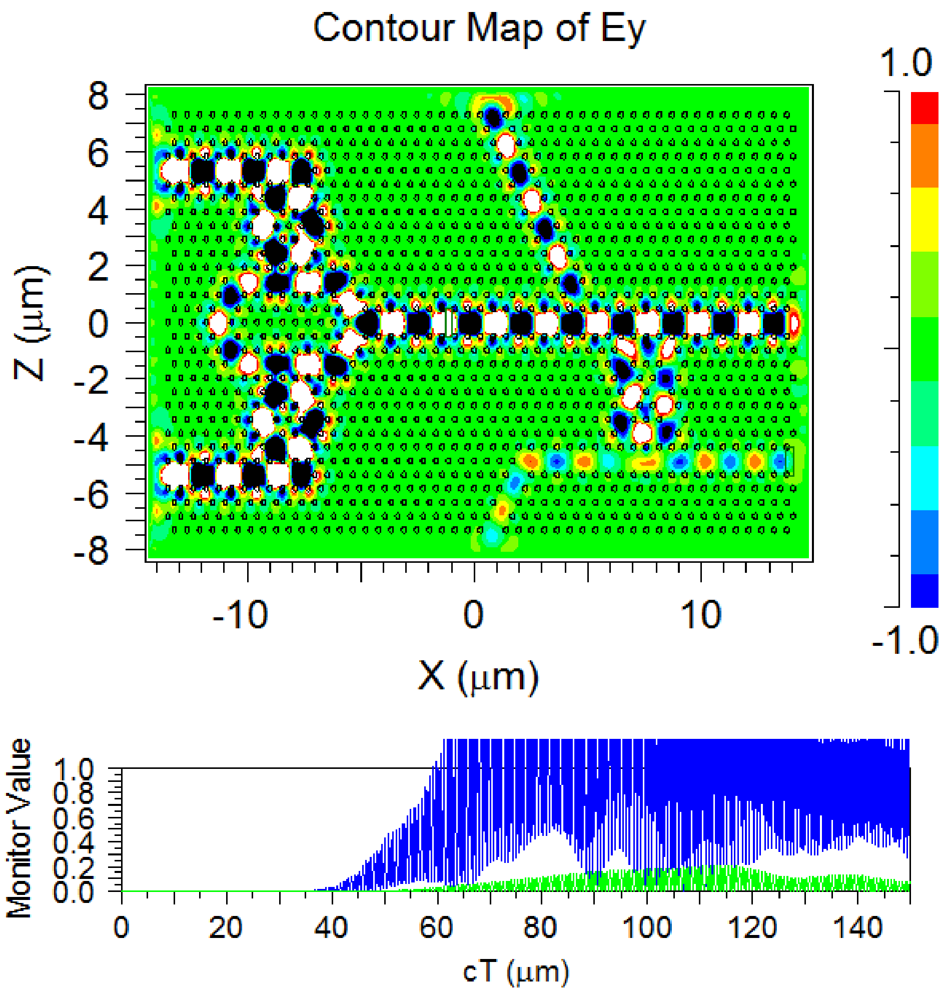

Figure 6.11: When M="1" , N="1" then Q="0"

6.4 Summary

An logic NOR gate which is designed by using logic OR gate and NOT gate is presented in this chapter. Also, the operation of logic NOR gate is observed. Firstly, the layout of OR and NOT gate are individually observed using Rsoft simulation tool and then these two structures are combined together to form NOR gate without using any external devices. The structure uses the non-linear Kerr effect for its operation and the whole structure is operated on wavelength equal to $1.40526875\mu m$.

Chapter 7

Conclusion and Future Scope

7.1 Conclusion

This chapter provides the summary of the research work done in this dissertation. Firstly, the conclusion have been made from this study and then the scope for the future research is discussed. The main results obtained in this thesis are concluded and summarized below:

- A design of optical logic OR gate based on 2D PhC using triangular lattice of silicon dielectric rods in air substrate is discussed. This structure has two inputs and a single output and it behaves like a OR gate. The structure of optical OR gate is simulated and analyzed by Rsoft simulation tool. The size of this structure is small(about $12.6\mu m \times 15\mu m$). Therefore, it can be used for PIC.

- A design of optical NOT gate based on 2D PhC using Kerr effect is discussed. The NOT gate is based on triangular lattice of silicon dielectric rods in air substrate. The NOT gate consists of one lower waveguide and upper waveguide and a single ring resonator. The size of this structure is small(about $21\mu m \times 27\mu m$) and the contrast ratio is about $6.9dB$. It operates at 1550 nm wavelength which is the third optical window in communication system.

- A design of optical NOR gate based on 2D PhC has been discussed. The structure is made from the combination of OR logic gate and NOT logic gate. This structure make use of triangular lattice and we use this technique of combining two logic gates OR and NOT gate to minimize the reflection losses. The size of the structure is about $50\mu m \times 31\mu m$. It uses non-linear Kerr effect. The Kerr coefficient is 1.5×10^{-16}.

7.2 Future Scope

During the course of this dissertation, several paths for continuation of this study became evident. The topics which were considered worthwhile are summarized below: These layouts of logic gate can be used to design complex logic circuits, future optical networks and communication system because these designs have high extinction ratio, compatible, compact size etc.

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