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Design and analysis of all-optical photonic crystal logic gates using a combination of Y T waveguides

Presented and publicly defended by

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Dedication

I present to you this humble work: To Almighty Allah, who has inspired and guided me on the right path. I owe what I have become to You; praises and thanks for Your mercy and compassion.

To my dear parents:

But no dedication will witness my deep love, great gratitude and great respect, because I can never forget the tenderness and sincere love with which they have always surrounded me since my childhood.

I also dedicate this humble work: To my religious brothers IMAD , SOUHIB , BADER EDDIN and ADJYAD , who have always been a support to me and a source of my happiness. May you always be a support for me that does not tend.

To my sisters, the fountain of love and tenderness, Lina and Alaa and HADJER, I love you.

To my dear friend Nadjet, may you always be proud of your family. May God grant you success.

To everyone I love, and to all the people who encouraged me and took the trouble to support me during this university year.

Soundous

Dedication

First and foremost, I want to thank Allah for all the mercy and blessings He has bestowed upon me, from being born a Muslim to guiding me to where I am today. Alhamdulillah.

To my mother, who has given me everything and more, I wouldn't be proud of who I am without you. You have stressed and prayed for this moment, so I dedicate all of it to you, my love.

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To my dear SOUNDOUS, you are the best partner I could ask for.

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Last but not least, thanks to young Nadjet. It brings tears to my eyes thinking of you while writing this. I know you are proud of what we have achieved so far, and may God give us the strength to achieve more. We have come a long way, and the pursuit of happiness is going well so far, thanks to God.

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Abstract

In this paper, AND, OR, NAND, NOR, XNOR, NOR, NOR, NOR, NOT, and XOR logic gate structures based on 2D photonic crystals were proposed and simulated using a T- and Y-shaped composite structure. Their optical engineering parameters have been optimized to enable them to exploit the 1550nm communication wavelength. These gates can compete with their predecessors in size, contrast ratio, response time, and ease of integration. The simulation results were analyzed using the finite difference time domain method (FDTD). The plane wave analysis method (PWE) calculated the band gap. We obtained a response time in the range of 0.2 ps at all studied gates.

Key words: Photonic crystal, Band gap, All-optical logic gate, bit rate, FDTD, contrast ratio, PWE, FullWAVE, BandSOLVE.

Résumé: Dans ce mémoire, des structures en cristaux photoniques 2D de portes logiques NAND, NOR, XNOR, NOR, NOR, NOT et XOR basées sure la combinaision des guides d'ondes de forme T et de Y ont été proposées et analysées. Leurs paramètres d'ingénierie optique ont été optimisés pour leur permettre d'exploiter la longueur d'onde de communication de 1550 nm. Ces portes peuvent rivaliser avec leurs prédécesseurs en termes de taille, de rapport de contraste, de temps de réponse et de facilité d'intégration. Les résultats de la simulation ont été analysés à l'aide dela méthode des différences finies dans le domaine temporel (FDTD). La bande interdite a été calculée à l'aide de la méthode d'analyse des ondes planes (PWE). Nous avons obtenu un temps de réponse de l'ordre de 0,2 ps pour toutes les portes étudiées.

Mot clé: Cristal photonique, bande interdite, porte logique tout optique, débit binaire, FDTD, rapport de contraste, PWE.

ملخص : في هذه المذكرة ، تم اقتراح ومحاكاة هياكل بوابات منطقية AND و OR و NAND و XNOR و NOR و NOT و XOR استناداً إلى بلورات ضوئية ثنائية الأبعاد، باستخدام هيكل مركب من الشكلين T و Y . كما تم تحسين معامِلاتها الهندسية الضوئية بما يمكّنها من استغلال الطول الموجي للاتصالات البالغ 1550 نانومتر. حيث انه من الممكن ان تكون هذه البوابات قادرة على منافسة سابقاتها في مجالها من حيث الحجم ونسبة التباين وزمن الاستجابة وسهولة التكامل. تم تحليل نتائج المحاكاة باستخدام طريقة المجال الزمني للفرق المحدود . وتم حساب فجوة النطاق باستخدام طريقة تحليل الموجة المستوية (PWE) . حيت تحصلنا على وقت الاستجابة يتراوح في حدود 0.2 *ps* عند كل البوابات المدروسة.

الكلمة المفتاحية: البلورة الضوئية، وفجوة النطاق، والبوابة المنطقية الضوئية بالكامل، ومعدل

البت، و FDTD ، ونسبة التباين، و ، PWE .

Contents

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List of abbreviations

PHC	Photonic crystal.
PHC*s*	Photonic crystals.
1D	One-Dimensional.
2D	Two-Dimensional.
3D	Three-Dimensional .
DFB	Distributed-feedback.
LED	Light-emitting diode.
PBG	Photonic band gap .
RI	Refractive index .
CR	Contrast ratio .
FDTD	Finite Difference Time Domain .
TE	Transverse Electric .
TM	Transverse Magnetic .

List of symbols

λ	Resonance wavelength.
λ_0	Wavelength in vacuum.
a	Photonic crystal period.
r	Photonic crystal radius.
R	Reflectivity.
n	Refractive index.
c	Speed of light in a vacuum.
Δ	Index contrast.
E	the electric field.
H	The magnetic field.
Q	Quality factor.
ϵ	Dielectric permeability.

General introduction

Telecommunications systems are considered a vital fabric of modern communication, which is the process of communicating with others using electronic equipment such as telephones, computer modems, and satellites. Since we live in the age of information technology, the demand for access to information services on a global scale is increasing dramatically. With the number of users, telecom operators are turning to optical technologies for optical communications, which are communications that use light to transmit information. This can be done visually or using electronic devices. In the mid-1990s, advances in nanotechnology-enabled the development of artificial materials that behave surprisingly well about electromagnetic waves, and the idea of controlling light was a scientific breakthrough. This led to the discovery of photonic crystals in 1987 [1] when E. Yablonovitch [2] and S. John [3] introduced the concept of photonic bandgap materials separately and in different contexts. It should be noted that one-dimensional periodic structures such as Bragg mirrors were used long before this proposal to control the propagation of light. Since then, a large number of studies have been conducted on the design, fabrication, and applications of photonic crystals, Research in photonic crystals today covers the most fundamental areas, such as spontaneous emission control, as well as application-oriented areas in guided optics. Of great importance to the scientific community, especially in the field of optics, the first photonic crystal was produced in 1991 [2].

Photonic crystals are periodic nonstructural materials that have the same effects on photon propagation as conventional crystals have on electron propagation: certain wavelengths can propagate while others cannot. Depending on whether the periodicity exists along one, two, or three axes, the crystal is described as one (1D), two (2D), or three dimensional (3D) [4].
Although the development of nonlinear optics at optical wavelengths dates back to the 1960s, it was not until the mid-1960s that it was applied to photonic crystals. The aim was to achieve the phase tuning condition necessary to obtain second-order nonlinear processes in electronic states, and it was not until the early 90s that the great boom in second- and third-order nonlinear phenomena in photonic crystals took place [5–7].
Despite the difficulties of fabrication, modeling, and characterization, applications of these photonic crystals at optical frequencies have largely gone beyond the initial idea of automatic emission control. Today they cover a wide range, from studying strong atomic/cavity coupling to optical bonding. Among the areas of use of photonic crystals are Photonic crystal fibers, Photonic Crystal Filters [8], Photonic Crystal Planar Waveguides [8], Sensors based on photonic crystal [9, 10], photonic crystal dividers [11–14], and photonic crystal logic gates.
Photonic crystal logic gates represent a specific application within the broader field of

photonic crystals, focusing on their use in optical computing and processing. These logic gates are designed to perform Boolean logic operations using light signals instead of electrical signals, offering advantages such as high speed, low power consumption, and potential integration with existing optical technologies, offering advantages such as high speed, low power consumption, and potential integration with existing optical technologies [15].

Much research work has been done on the realization and optimization of photonic crystal-based logic gates. A few of them are multi-mode interference (MMI), self-harmonizing effect, photonic crystal ring resonators and PhC waveguides, and also the combination of PhC ring resonators. To further optimize the performance of photonic crystal-based logic gates, we propose in this dissertation the structures using combination waveguides of Y-shape and T-shape.

This dissertation is organized as follows: In the first chapter we talked about the basic principles of photonic crystal synthesis, then the different types of photonic crystals and their properties, the principle of opening the photonic band gap, and the most important applications of photonic crystals, and the chapter ends with a presentation of some defects in photonic crystals.

In the third chapter, we presented the design of photonic crystal-based photonic logic gates using dissertation waveguides with a combination of Y-shape and T-shape. This design requires the use of basic elements such as microsteering, ring resonator, and resonant cavity. The proposed designs are simulated using the finite-difference time-domain method (FDTD) in 2D.

Chapter 1

Photonic crystals : overview, properties and applications

Contents

1.1 Introduction

Indeed, the optical properties of periodic structures are ubiquitous in nature, manifesting in mesmerizing displays such as the shifting colors of opals and the intricate patterns adorning butterfly wings. These phenomena are a testament to nature's adeptness at harnessing the principles of photonic crystals over millions of years [16], but humans have only recently started to realize their potential. One-dimensional periodic structures in the form of thin film stacks have been studied for many years [17], but three-dimensional photonic crystal was first proposed by Yablonovitch [18] and John [3] in 1987. Yablonovitch proposed that three-dimensional periodic dielectric structures could exhibit an electromagnetic bandgap - a range of frequencies at which light cannot propagate through the structure in any direction. He also predicted that unwanted spontaneous emission within a semiconductor can be prevented by structuring the material so that the frequencies of these emissions fall within a photonic bandgap; since no propagating states exist at that frequency, emission is effectively forbidden. John [3] showed that many of the properties of PhCs survive even when the periodic lattice becomes disordered. In such structures, if the index contrast is sufficiently large, strong light localisation can still occur, in analogy to the electronic band gaps of amorphous semiconductors. Perhaps more relevant to much of the PhC research that has followed, and to the topic of this thesis, was Yablonovitch's [18] interpretation of the cavity modes that can be introduced into a periodic structure by creating a defect or "phase slip". While resonant cavities in distributed feedback lasers had had already been demonstrated using this approach [19], Yablonovitch showed that modes could be localised in three-dimensions and explained the effect in terms of defect states in the photonic bandgap. From this observation, and the initial proposals for limiting spontaneous emission, the concept of controlling light with periodic structures has developed rapidly into a topic of worldwide research.in .this chapter we will have a general view over the photonic crystals.

1.2 History of photonic crystals

Lord Rayleigh's pioneering work in 1887 marked the first exploration into the electromagnetic wave propagation within one-dimensional periodic structures, such as multiplayer films, known as Bragg mirrors. His studies revealed the existence of band gaps in such systems, laying the groundwork for understanding the behavior of light in periodic structures. Over the following decades, one-dimensional periodic systems continued to be extensively studied and found applications in various fields. Reflective coatings utilized the reflection band corresponding to the photonic band gap, while distributed feedback (DFB) diode lasers employed crystallographic defects within the photonic band gap to define laser wavelengths. However, it wasn't until 100 years later, in 1987, that Eli Yablonovitch and Sajeev John proposed the possibility of two- and three-dimensional periodic crystals with corresponding band gaps. This groundbreaking insight sparked a surge of interest and research worldwide, with numerous potential applications emerging, including LEDs, optical fibers, nanoscopic lasers, ultra white pigment, radio frequency antennas, reflectors, and photonic integrated circuits. Recent advancements in the field have seen the realization of Yablonovitch's predictions, with researchers successfully demonstrating the control of light beams using three-dimensional photonic crystals. These developments hold immense potential for various applications, including quantum optical systems, miniature lasers for displays and telecommunications, solar cells, and future quantum computers. The ability to control the pace of light emission opens up new avenues for technological innovation and advancement [20].

1.3 Defining photonic crystals

Photonic crystals are materials characterized by the periodic modulation of the dielectric constant along one, two, or three directions of space. Correspondingly, one speaks about one-, two-, and three-dimensional (1D, 2D, and 3D, respectively) photonic crystals, they utilize the existence of photonic band gaps that form from periodicity among materials to limit the propagation of light along certain wavelengths to produce desired effects [21].

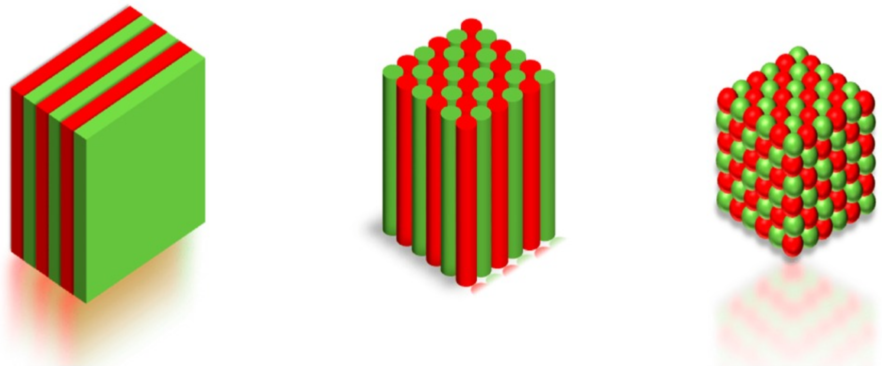


Figure 1.1: Sketch of the representation of the three kinds of photonic crystals. The different colors represent materials with different dielectric constants.

1.3.1 Maxwell equations

Maxwell's Equations are a set of 4 complicated equations that describe the world of electromagnetic. These equations describe how electric and magnetic fields propagate, and interact, and how objects influence them [22]. In a vacuum with no charge or current, Maxwell's equations are, in differential form:
• Gauss' law of electricity is shown in (1.1)

$$\nabla \times \mathbf{E} = 0 \tag{1.1}$$

• Gauss' law of magnetism 1.2

$$\nabla \cdot \mathbf{B} = 0 \tag{1.2}$$

• Faraday's law of induction 1.3

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{1.3}$$

• Ampere's law 1.4

$$\nabla \times \mathbf{B} = \mu 0 \in 0(\frac{\partial \mathbf{E}}{\partial t}) \tag{1.4}$$

• Gauss' law of electricity 1.5

$$\nabla \cdot \mathbf{D} = \rho \tag{1.5}$$

• Ampere's law 1.6

$$\nabla \times \mathbf{H} = \mathbf{J}\frac{\partial \mathbf{E}}{\partial t} \tag{1.6}$$

In the first equation,ρ is the free electric charge density. In the last equation, J is the free current density.

1.3.2 Classification of photonic crystals

The number of directions of periodicity of the refractive index (RI) indicates the type of photonic crystal:
• Periodicity in one direction: 1D photonic crystal or Bragg mirror.
• Periodicity in two spatial directions: 2D photonic crystal.
• Periodicity in all spatial directions: 3D photonic crystal.
Schematic representations of the CP (photonic crystal) structures are presented in the following figure (1.2):

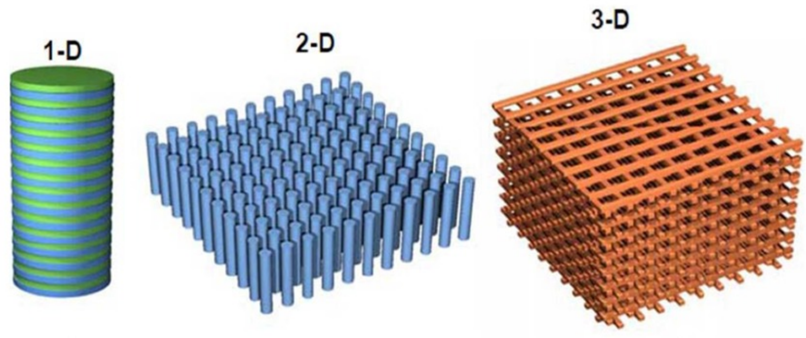


Figure 1.2: Schematic illustrations of photonic crystals 1D 2D and 3D

1.3.3 Photonic crystals band gap

The crystals have band gaps that allows some specific wavelengths of light to pass, permitting the unparalleled control of the behavior of light. They are composed of periodic dielectric, metallo-dielectric or superconductor micro structures or nano structures. Dielectric materials are essentially electrical insulators that are polarize with an electric field and can affect electromagnetic wave propagation by defining 'allowed' and 'forbidden' electronic energy bands. The solid lines correspond to the proprietary modes with TE polarization, while the dashed lines correspond to the proprietary modes with TM polarization. The photonic band gap a rise when the wavelength roughly of the order periodicity, λ=a (a is periodicity [23].

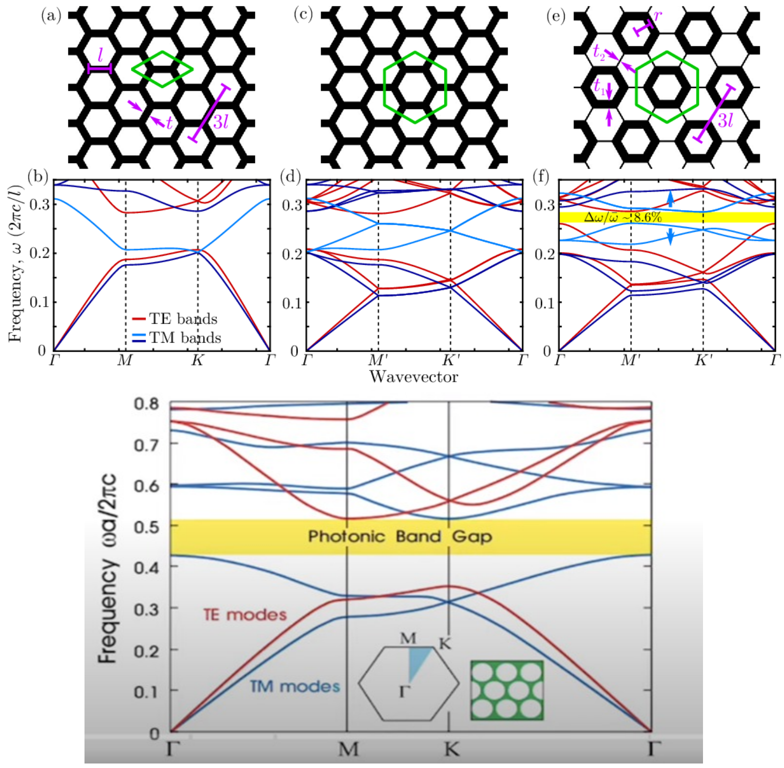


Figure 1.3: Photonic band gap in supercell photonic crystal.

1.4 Type of photonic crystals

Photonic crystals can be realized in different dimensions, which are discussed in the following sections.

1.4.1 One-dimensional photonic crystals

It can also be named Bragg mirrors used to achieve lossless mirrors or filters. One frequently just ignores the additional spatial dimensions by considering only light propagating into exactly opposite directions, coupled to each other by the periodic refractive index modulation [24].

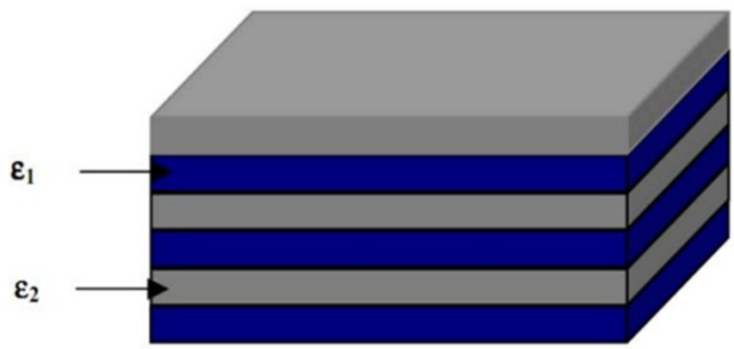


Figure 1.4: One-dimensional structure .

1.4.2 Two-dimensional photonic crystals

Two-dimensional photonic crystals are periodic structures constituted of holes etched in dielectric slabs with square, hexagonal or honey-comblattices. [25]A one-dimensional photonic crystal structure, containing layers of two materials with different refractive index.

1.4.2.1 Disconnected structures

Characterized by a higher refractive index n_1 of the elementary pattern compared to the inter-pattern space's n_2, these structures consist of periodically aligned dielectric or metallic rods in the air [6] figure 1.5 (a) .

1.4.2.2 Connected structures

Comprising air holes drilled into a dielectric membrane, these patterns exhibit a refractive index n_1 lower than the dielectric matrix's n_2, aiming to create a periodic refractive index variation figure 1.5 (b).

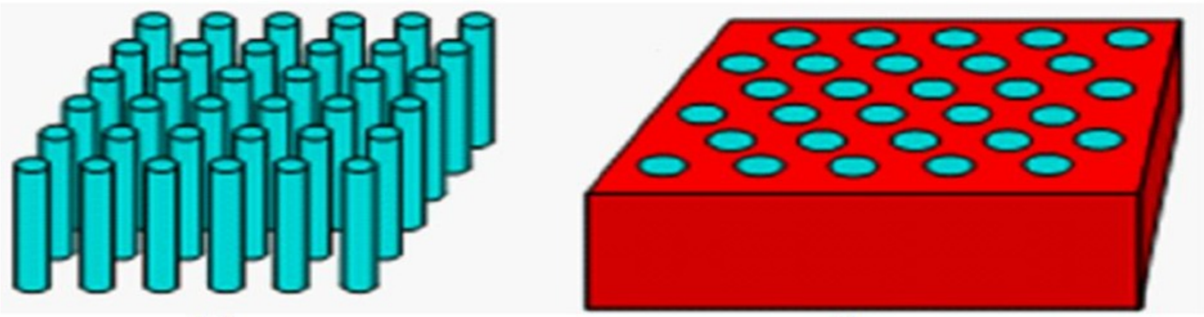


Figure 1.5: : Structure of (a) dielectric rods in air and (b) air holes in dielectric region.

1.4.2.3 Square lattice structures

This lattice is highly sensitive to the angle of incidence and the polarization of electromagnetic waves. It has been shown that this lattices difficult to simultaneously achieve a photonic band gap for TE and TM polarization's.

1.4.2.4 Triangular lattice structures

The structure shown in Figure 1.6 (b) offers a better compromise when the filling factor is high,meaning when the hole diameter is close to the lattice period. It is less sensitive to the angle of incidence than the square structure.

1.4.2.5 Hexagonal lattice structures

This lattice can be obtained by removing certain nodes from the triangular lattice. It offers the best compromise between technological constraints and structure performance. Two variations of the hexagonal lattice can be discerned: the structure in 1.6 where all nodes are identical and spaced by a similar period 'a', and the structure in Figure (d) where one node differs from its neighbor in nature or dimension. This structure allows for relatively wide photonic band gaps [26].

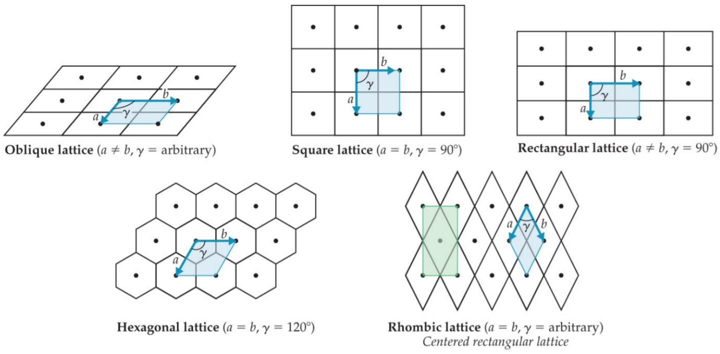


Figure 1.6: : Structures of 2D photonics crystalis .

1.4.3 Three dimensions photonic crystal

This photonics crystalis fabricated in form of Spheres of silicon arranged a diamond structure, in 1993 yoblonovitch came up with a design that will be named after him later on, the principle design of yoblonovitch is to create holes in vertical directions also in three different directions 35°,26°, the hexagonal array will be drill in tree directions in the same point this will allow the band energy to be interdict in all directions .

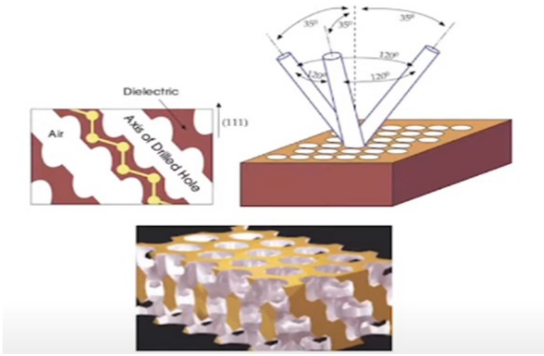


Figure 1.7: Structure of yoblonovitch.

1.5 Defects in photonic crystals

In this paragraph there is a simple case of a planar defect in a photonic crystal and the calculation is done using the matrix transformation method. Point defects are usually called high cavities, H for hexagonal shape and i for width which is expressed as the number of missing rows on one side of the hexagon of holes (or columns) in a binary CP Dimensions. Disadvantages Extensions called W guides for the wave guide and for the guide view Plane wave evolution which is often used to determine optical properties [27]. As in semiconductors, defects can be deliberately introduced into photonic crystals. Defects in semiconductors have the effect of introducing permitted energy levels into the band gap.

In the case of photonic crystals, the creation of defects in the periodicity of the structure also leads to permitted energy levels in the band gap [28].

1.5.1 Punctual defects

There are many ways of creating point defects in photonic crystals, including the removal, addition or medication of one or more crystal units. To use the terminology of solid-state physics, we then create lacunaire or substitutions defects. In all the cases shown in this figure 1.8, optical cavities are created, the resonance modes of which are positioned in energy within the forbidden bands of the crystal [6].

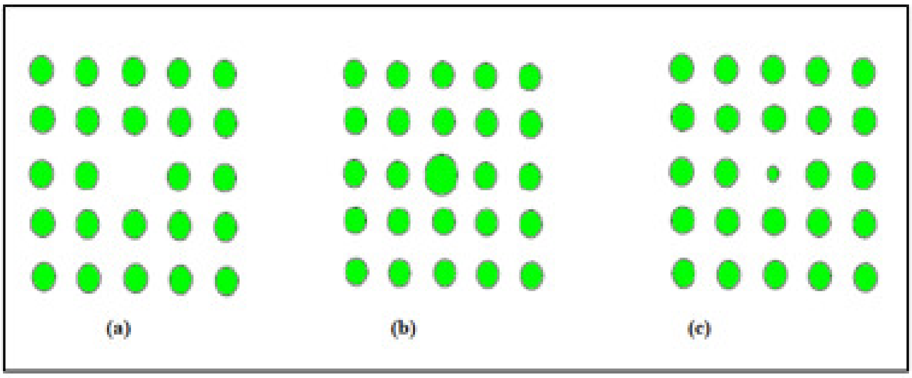


Figure 1.8: Punctual defects (a), Lacunar defects (b) and (c) Substitution defects.

1.5.2 Linear defects

These defects enable diffracting wave guiding, also known as extended defects, of dimensions 1, 2 or 3, and can obviously only be obtained in crystals of at least equivalent size. Among these defects, 1D defects (W1) see figure 1.17 1.9 are certainly the most widely studied, as they are intended to be used as light guides within a given crystal. We can also imagine 2D (W2) or 3D (W3) defects made up of a series of W1 guides, placed end-to-end and oriented in different directions, so as to carry light along all possible paths within the crystal. The basic example is the linear wave guide W1 in a 2D photonic crystal. One way of realizing such a wave guide is to place regularly spaced, coupled point defects in one direction of the 2D crystal. The coupling between an infinite number of resonators leads to a band of propagation permitted in the direction of alignment. This type of coupled-resonator guide was proposed in 1999 [5].

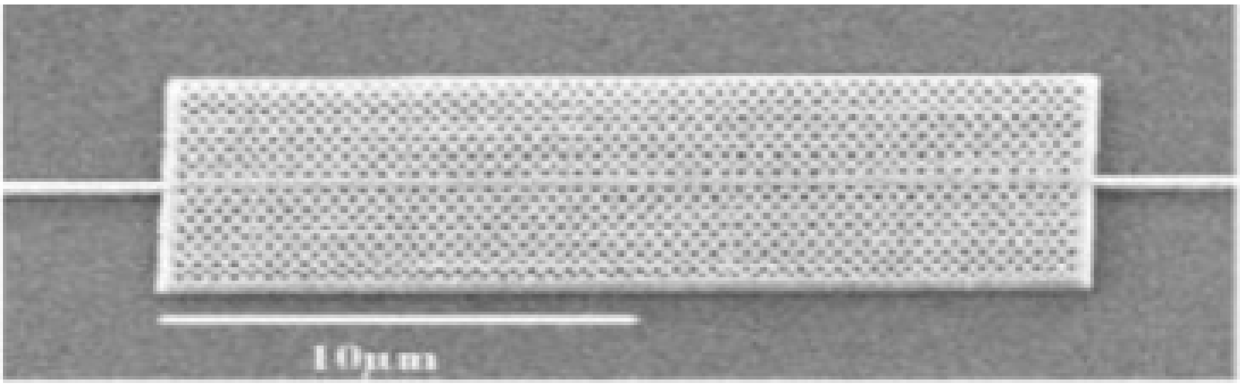


Figure 1.9: Example of a W1 guide with a hexagonal air-hole photonic crystal on a silicon-on-insulator substrate.

1.6 Applications of photonic crystal

1.6.1 Photonic crystals fibers

A core consisting of slightly higher refractive index and a cladding consisting of slightly lower refractive index and because of the difference in refractive indices the light undergoes total internal refraction while in propagates to the through the fiber and then, it propagates very large distances.The figure 1.10 bellow shows a stack of various preforms and applied heat to the stack and when pulled, it results in obtaining glass and holes in between .

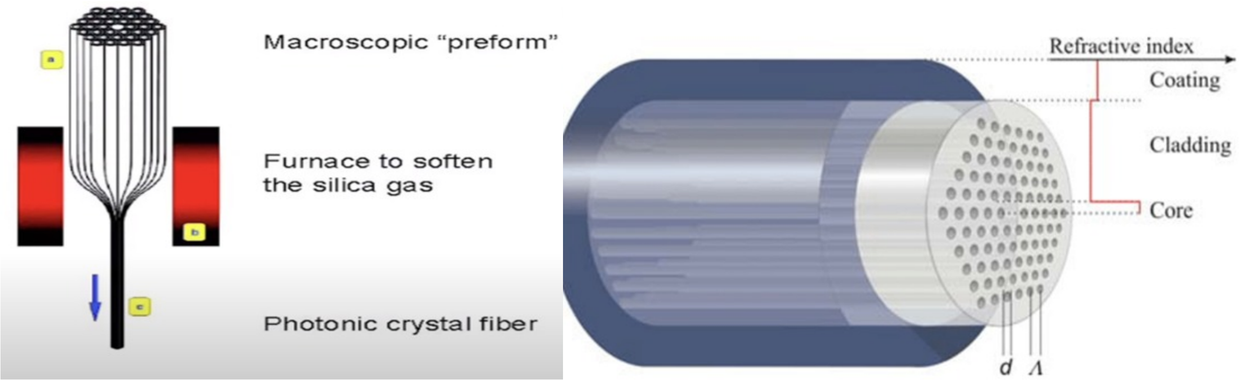


Figure 1.10: Photonic crystals used in fibers.

1.6.2 Photonic crystal filters

Multiple streams of data carried at different frequencies F1, F2, etc. in the figure 1.11 bellow(yellow) enter the optical micro-chip from an external optical fiber and are carried through a wave guide channel (missing row of pores). Data streams at frequency F1 (red) and F2 (green)) tunnel into localized defect modes and are routed to different destinations [8].

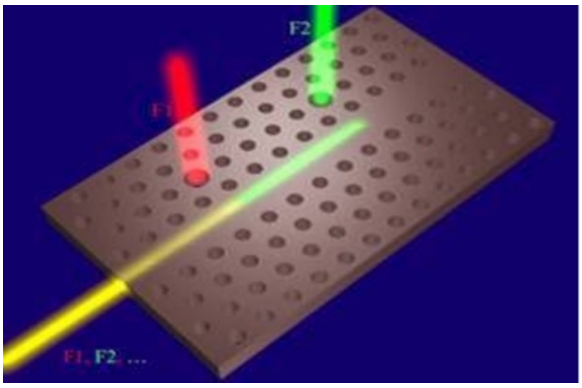


Figure 1.11: Photonic crystals filter.

1.6.3 Photonic crystal planar wave guides

Creating a thin band radius for fiber can be difficult. conventional fibers struggle with bend radii due to total internal reflection failures. Photonic crystal wave guides use line defects to guide light within the band gap, facilitating lossless propagation around bends. This method ensures efficient transmission even with sharp bends [8].

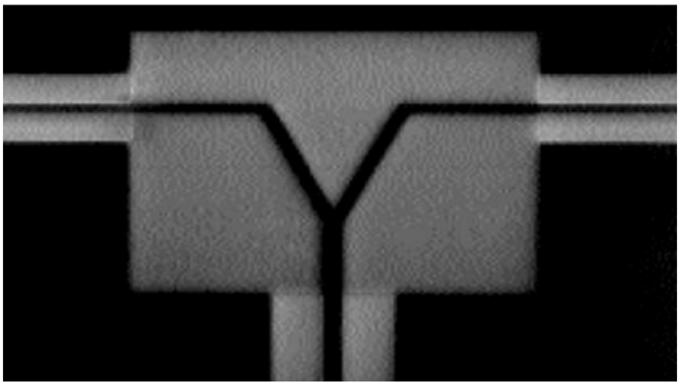


Figure 1.12: Photonic crystal Planar Wave guides.

1.6.4 Sensors based on photonic crystal

Several sensors based on Phc have been studied and developed for a wide range of sensing applications. Sensors based on CPs fibers are novel optical waveguide structures that contain a network of air holes along the fiber. A small defect in these structures provides an optical path with an optical spectrum that can propagate at a specific frequency with high sensitivity [9] .

1.6.5 The photonic crystal divider

The photonic crystal divider simultaneously separates and distributes light to different parts of the optical circuit. Firstly, the Y-junction type divider was studied.Y junction divider was studied, comprising an input guide, a Y junction portion and two or four output guides. Any number of outputs can be obtained by cascading them. This type of component has the advantage of offering a flat spectral response over a very wide wavelength range, and theoretical analysis of design parameters has been carried out by Fukazawa.

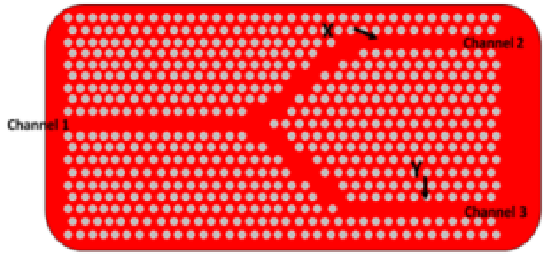


Figure 1.13: The Y (1x2) photonic crystal divider

This component is therefore capable of splitting a signal from a single waveguide to several output guides [11].

1.6.6 Photonic crystal logic gates

Photonic crystal logic gates indeed hold significant promise for the advancement of optical computing. By leveraging the unique properties of photonic crystals, researchers aim to develop compact and efficient optical logic gates that can revolutionize computing technology.

1.7 Conclusion

Photonic crystals are materials whose dielectric index varies pe-radically on the wavelength scale, in one or more directions in space. Periodicity can be one-dimensional, two-dimensional or even three-dimensional. In this chapter, we have presented a basic overview of photonic crystals, their different types and applications. The choice of photonic crystals is due to the fundamental characteristics of BIP. Consequently, the majority of applications derive from the band gap, which has emerged as an interesting property also present in the world of photonic crystals. Next, we discussed the different types of defects that exist. Finally, we end this chapter with some potential gaps.

Chapter 2

Photonic crystal-based logic gates

Contents

2.1 Introduction

Photonic crystal-based all-optical logic gates (CPs) have attracted worldwide attention due to their low switching power and very high data transfer speed. To date, many efforts have been made to design all-optical logic gates, while few studies have focused on the development of multifunctional structures. These architectures provide great flexibility in the design of digital systems. In this chapter, we will introduce the concepts of different photonic crystal logic gates, their seven types, their functional parameters, and some of their application areas. Finally, we will conclude this chapter with some of the calculation methods used in this work, namely the FDTD method and the PWE method .

2.2 History of photonic crystal-based logic gates

The history of logic gates dates back to the mid-19th century with the development of Boolean algebra by the British mathematician and logician George Boole. Boole's work laid the foundation for modern digital logic and the design of electronic circuits. However, it wasn't until the 20th century that practical implementations of logic gates began to emerge. In 2004, Locatelli and Cuesta-soto proposed optical switches based on directional couplers in photonic crystals in two different research studies [29]. Zhu implemented the AND logic gate based on a photonic crystal in 2006. Several rods with a non-linear Kerr effect were used to control the function of the AND gate in their structure. With regard to other photonic crystal logic gates, Zhang et al, in 2007, proposed OR and XOR logic gates based on the property of (self-parallel) photonic crystals [30]. Shinya developed an optical memory on a photonic crystal chip in 2008. In the same year, Liu proposed a photonic crystal half-adder structure. An XOR logic gate based on interference of incoming beams, this work was published by Lee. Andalibet Granpayehen 2009, published a scheme for the AND logic gate using a ring resonator structure based on nonlinear photonic crystals. In the same year, Jung proposed another design, in which nonlinear photonic crystal cavities were used to create logic gates. For coding, Lee also proposed the structure of a 2×4 encoder. Various concepts for implementing photonic crystal-based logic gates have been developed over the last decade. These devices have been proposed to optimize the functional parameters of logic gates by reducing power consumption, increasing bandwidth, and improving contrast ratio. To improve and implement the properties of photonic crystal-based logic gates, they use different materials and semiconductors. Other designs have been launched using the property of multi mode interference, to realize photonic crystal-based logic circuits. One such circuit is proposed by Ishizaka . to realize AND and XOR logic gates ékouddad2022contribution.

2.3 Defining logic gate

A logic gate is a device that acts as a building block for digital circuits. They perform basic logical functions that are fundamental to digital circuits [31]logical gates are used in most of the modern electronic digital devices and also are used to carry out logical operations on single or multiple binary inputs and give one binary output.

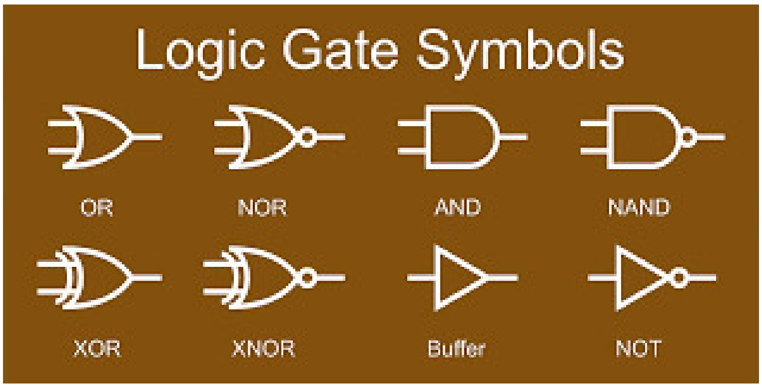


Figure 2.1: Logic gate symbols

2.4 Logic gate representation

As it was mentioned in the previews paragraph logic circuits are normally composed of 'gates'. It is that the logic gates produce pulses of electrical current (1s and 0s). logic gates are presented in three ways .

2.4.1 Truth tables

Truth tables are columns made to simplify and represent how the logical gates work, every truth tables has two sections indicatethe outputs or results of all possible inputs combinations. the structure inputs and outputs presented by the values 1s and 0s. If there are n inputs then there are maximum 2n (2 to the power n) possible states or unique combination of inputs. For example with three inputs there are 22=8 possible combination of inputs.

2.4.2 Logic circuit diagram

Logic circuit diagram is used to describe and graphic design of the logic gate. Each gate is represented differently to ensure clarity. thereby minimizing confusion during application.

2.4.3 Boolean expression

Boolean algebra can be used to write a logic expression in the form of an equation. '+' means OR, So P+Q is same as P OR Q '.' means AND, So P.Q is the same as P AND Q A means NOT A, Sometimes it is called the complement of A means XOR, So P Q means P XOR Q **??**

2.5 Types of logic circuits

Logic circuit for digital system is categorized into two main categories.

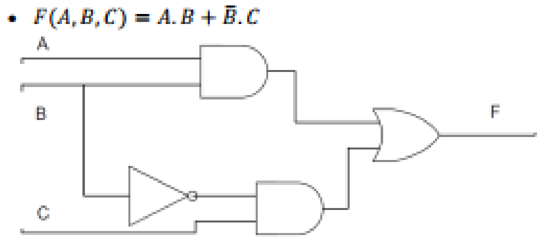


Figure 2.2: Example of a logic circuit diagram based on an array of logic gates

2.5.1 Computational logic circuit

Computational logic circuits consist of logic gates whose outputs at any time are determined directly from the present combination of inputs without regard to previous output **??**.

2.5.2 Sequential logic circuit

Sequential circuits employ memory elements i.e. binary cells in addition to logic gates. The output of an sequential circuits are a function of the inputs and the state of the memory elements. The state of an memory elements, in turn, is a function of previous outputs.

2.5.3 The example of Logic circuit diagram

This is the translation of the logic function into an electronic diagram, and consists in replacing each logic operator by the corresponding logic gate .

2.6 Applications of logic gate

Logical gates are mainly used in most electronic or circuits devices and industrial plants as-well as in frequency measurement In digital electronics, logical gates have the functionality of processing and manipulating data. Each gate can be specialized for a specific task, for example,AND gates are used as Enable gate and Inhibit gate. Enable gate means acceptance of data through a pathway while Inhibit gate is the opposite of that process which means rejection of data through a pathway XOR and XNOR gates are used in identity generation and identity check operations. NOT gates are also called inverters because they switch the output given to them and show the reverse outcome OR gates can be use din an industrial plant, if one or more than one specification goes beyond the safe value, some security measures must be done [32] .

2.7 Advantages and disadvantages of logic gate

2.7.1 Advantages

Logic gates are known for their speed and energy efficiency, making them essential components in digital circuitry. They streamline operations, reducing the required number of I/O ports for micro controllers. Moreover, logic gates facilitate simple data encryption and decryption processes. These gates operate based on Boolean Algebra, which simplifies circuit design and makes it more cost-effective. With logic '1' representing true and logic '0' indicating false, the distinction between the two states is clear, enabling precise control and manipulation of digital signals .

2.7.2 disadvantages

the main disadvantages of logical gates is the limitation of the applicability, compared to analog circuits logic circuits attend to consume more energy leading an increase of heat production, this heat can impose limitations the practical use of logic circuits. logic circuits operate within constrained voltage ranges .

2.8 Functional parameters

The performance of photonic crystal-based optical devices is evaluated using the following function parameters .

2.8.1 Transmission efficiency (η)

Transmission efficiency is used to estimate the output signal power or signal intensity level. It is one of the critical factors in photonic crystal-based encoders and decoders. The equation is used to calculate transmission efficiency .

$$\mathrm{T}ransmissionefficiency = \frac{\mathrm{P0}}{\mathrm{P}i} \tag{2.1}$$

2.8.2 Contrast ratio

contrast ratio (CR) is a property of a display system, defined as the ratio of the luminance of the brightest shade (white) to that of the darkest shade (black) that the system is capable of producing.

$$\mathbf{C} = 10log\frac{\mathrm{P}on}{\mathrm{P}off} \tag{2.2}$$

2.8.3 Response time and bit rate

The delay in transmission for t1 to reach 0.1 of the average and the delay in transmission for t2 to reach 0.9 of the average power are the two parts that make up the response time.

2.8.3.1 Response time

$$\mathrm{R} = 4t2 \tag{2.3}$$

2.8.3.2 Bit rate

$$\textbf{Bit Rate(BT)} = \frac{1}{ResponseTime} \tag{2.4}$$

2.8.4 Insertion loss

$$\textbf{Insertion Loss(dB)} = 10log\frac{Pin - Pout}{Pin} \tag{2.5}$$

2.8.5 Propagation loss

The insertion loss to waveguide length ratio is used to define propagation loss. It is provided by propagation Loss:

$$\textbf{propagation Loss} = \frac{LengthoftheWa}{InsertionLossvelength} \tag{2.6}$$

2.8.6 Crosstalk

Crosstalk is a disturbance caused by the electric or magnetic fields of one telecommunication signal affecting a signal in an adjacent circuit.

$$\textbf{Cross Talk} = = 10log\frac{Plow}{Phigh} \tag{2.7}$$

Plow represents the lowest normalized power at the output port, while Phigh represents the highest power at the output port [33].

2.8.7 Data rate

The reciprocal of the steady-state time is the data rate. To calculate the data transfer rate, the time response of the output signal can be used .

2.9 Different photonic crystal logic gate concepts

Scientific research on CPU-based optical logic gates has been divided into three main categories .

2.9.1 Interference-based logic gates

Constructive and destructive interference occur when the phase difference and path difference are, respectively, equal to [2nπ.n λ] . [(2n + 1)π] . [(2n + 1)λ/2] To guarantee stable interference in photonic structures, waves of the same frequency must be emitted with a stable, controllable relative phase. These waves must be directed inside the structure in such a way that they overlap in certain areas of the structure, causing interference at that point. As a result of this interference, and depending on the initial relative phase between the input fields, the superposition of waves may be constructive in one or more output channels and destructive in other output channels. this is illustrated in the figure 2.3 [7].

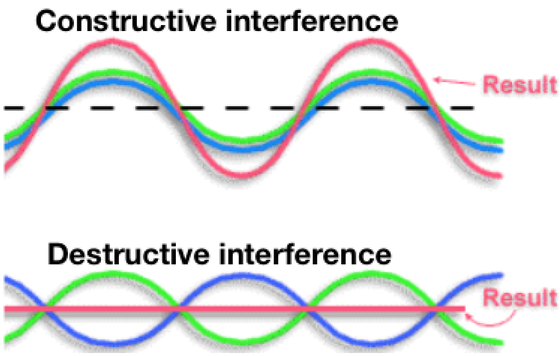


Figure 2.3: Destructive and constructive interference between waves.

2.9.2 Resonance-based logic gates

The waves are oscillating in small cavities that result from a point defect in the photonic crystal. The use of resonant tunnel filters is an ideal solution for creating logic gates. These filters consist of cavities and linear wave guides with low power consumption and high speed. Circular resonators are used in the design of optical devices such as switches and cam filters. The quality factor "Q" of a circular resonator, which indicates the light limitation of the resonator, is a key factor in determining the switching performance of all-optical circuits. A trade off must be made between maximizing Q and minimizing coupling when fabricating all-optical devices using ring resonators fig 2.4 . At the resonant wave length, the optical sensors of the wave guide input by the ring resonator are transmitted to the output wave guide, thereby performing the filtering function. The resonant wave length of the ring resonator depends on the optical geometric parameters of the ring resonator [7].

2.9.3 Logic gates based on auto-collimation

The auto-collimation phenomenon is independent of the intensity of the incoming radiation and does not require a complete optical band gap compared to photonic crystal waveguides, nor a side plate to prevent beam deflection and refraction, unlike photonic crystal waveguides which operate with an optical band gap. Consequently, devices based on auto-collimation have great potential for optical integrated circuits. One method of placing emission beams in parallel in a photonic crystal structure is to reduce the radius of

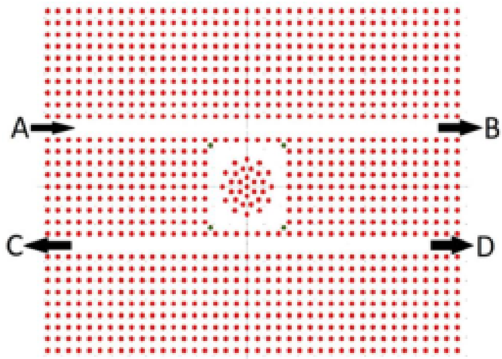


Figure 2.4: Photonic crystal ring resonator.

the rods rather than removing them to create a linear defect. This reduction eliminates total reflection, leaving only partial reflection of the wave. It is assumed that there is a phase difference between the reflected and transmitted beams. So, if another auto-collimation packet with an appropriate initial phase is introduced, the transmitted or reflected packets may cause constructive or destructive interference, resulting in interference in switch and logic gate performance [34].

2.10 All-optical logic gates based on photonic crystals

Photonic crystal-based waveguides and micro cavities are used to build logic gates, including all-optical logic gates such as NOT, AND, NAND, NOR, XOR, XNOR, OR.

2.10.1 Interference-based all-optical logic gates

In work [35] they proposed the design of XNOR, XOR, OR, and NAND gates using photonic crystals with square geometry and silicon rods suspended in air. Five rows were removed to create the "W5" waveguide. The structure consists of 11×15 cylindrical trees. The structure has two inputs A and B and one output Y. A radius of 0.2a (a = 600 nm) was chosen. Depending on the applied phase, constructive or destructive interference occurred at the output. When the phase difference between the input signals was 0, a high intensity signal was received at port Y. When the phase difference between the input signals was π, a high intensity signal was received at port Y. When the phase difference wasπ, the two input signals did not interfere with each other and one of them was reflected on input ports A and B, producing a small amount of light at the output port. When the phase difference was nπ/2, the light from input ports A and B overlapped and reached the same intensity at output port Y. Using different phase combinations, XOR, OR, NAND, and XNOR gates were realized. The contrast ratio obtained was 40.41 dB for the XNOR/XOR logic gates and 37.40 dB for the OR/NAND gate at a wavelength of 1550 nm, with a latency of less than 0.131 ps figure 2.5.

2.10.2 Resonance-based all-optical logic gates

In work [36] they proposed the design of NAND gates using the Kerr-type nonlinearity concept with a photonic crystal-based ring resonator. The structure consists of 33 × 26

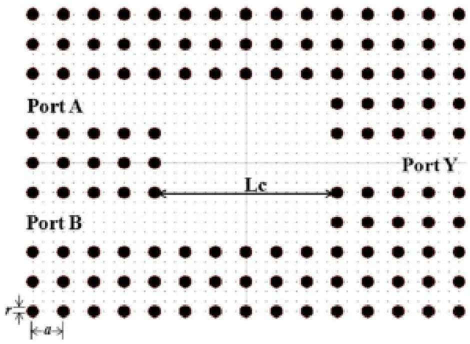


Figure 2.5: Structure of ports XNOR, XOR, OR and NAND in work [35] .

chalcogenide glass rods. The structure has three inputs A, B, and BIAS (reference signal) and one output OUT A radius of 0.2a was chosen where the period of the network "a" is 640 nm. The resonance wavelength is 1554 nm. When the power is 0.5 kW / µm, the refractive index changes due to the Kerr effect. This causes a change in the resonant wavelength of the ring resonator, preventing the transmission of the light wave at the output. When the input power of the ring resonator is less than 0.5 kW / μm^2, a resonance occurs in the ring, and the signal is routed to the OUT port output; otherwise there will be no signal at the gate output, confirming the operation of the NAND gate.

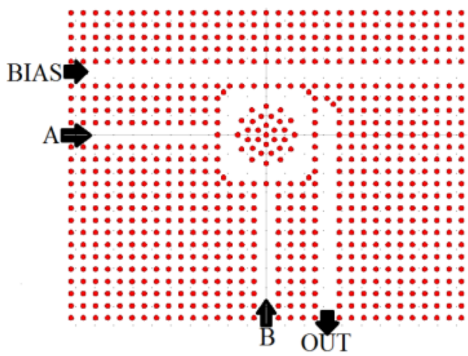


Figure 2.6: The structure of a NAND port using a non-linear materiel for efficient operation [36] .

2.10.3 Self-collimating all-optical logic gates

The photonic crystal structure in Figure A consists of a triangular lattice of cylindrical silicon rods with an airy background. With radius r = 0.35a and dielectric constant ∈ = 12.0. A linear defect is created in theγ-X direction by reducing the size of the 25 holes to 0.274a. When the phase difference between the two input beams is 2kπ+π/2, output O1 acts as an OR gate and O2 as an XOR gate. Figure B. When the phase difference is 2kπ-π/2 the output O1 acts as an XOR gate and O2 as an OR gate. Figure C. The highest contrast ratio obtained was 17 dB [30].

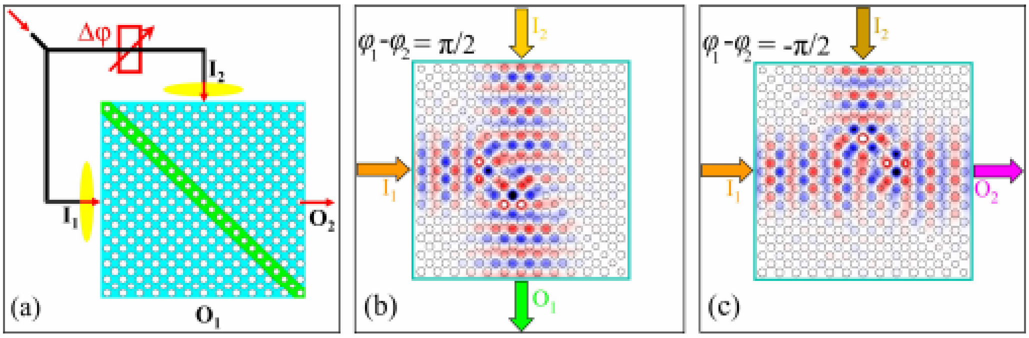
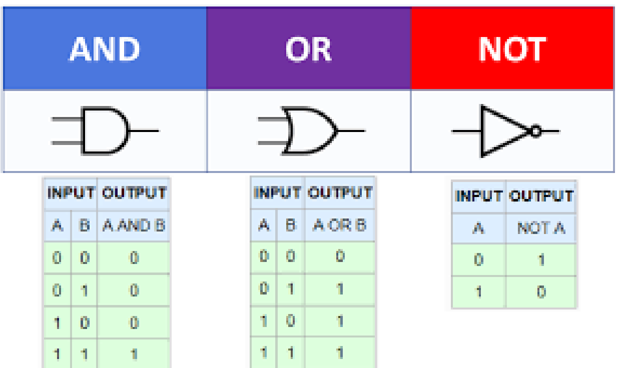


Figure 2.7: (a). Schematic diagram of the switch. Two rays with different phases are incident on input faces I1 and I2. (b) and (c) Simulated steady-state field distribution for polarized mode E at 0.194(a/λ) when the incident rays propagate along the γ-M direction. The phase difference ϕ1 - ϕ2 of the two incident beams are defined asπ/2 and -π/2, respectively .

2.11 Representation of basic logical functions.

2.11.1 The basic logic gates

AND gate is a digital logic gate with two or more inputs and one output that performs a logical coupling operation. When all inputs are true (1), the output of the AND gate is true (1). If one or more of the inputs of the AND gate are false (0), the output of the AND gate is false (0).
The OR gate preform an addition of the inputs operation where the output will be zero or down only if the inputs are down meaning 0 in the rest of the cases the output will remain 1 .
The NOT gate is the most basic gate out of them all, only one terminal is preformed. it operates simply by reversing the single input if it is 1 the output will be 0 , if the input is 0 the output is 1 .



INPUT		OUTPUT
A	B	A AND B
0	0	0
0	1	0
1	0	0
1	1	1

INPUT		OUTPUT
A	B	A OR B
0	0	0
0	1	1
1	0	1
1	1	1

INPUT	OUTPUT
A	NOT A
0	1
1	0

Figure 2.8: Truth tables of basic logic gates.

2.11.2 The secondary logic gates

The NAND gate is a combination between AND gate and NOT gate which leads to reversing the output of the AND gate giving us output of 1 in all cases except the input A and B being 1 shown in the figure A bellow.
NOR is the combination or Inversion of the logical OR gate and is also a universal logic gate. When the inputs are low or false, the resultant output is high or true [32].
The XOR gate is also known as exclusive NOR gate. the truth table of XOR shows that, if any input is high, the result is high or true.

X	Y	AND(X,Y)	OR(X,Y)	NAND(X,Y)	NOR(X,Y)	XOR(X,Y)
0	0	0	0	1	1	0
0	1	0	1	1	0	1
1	0	0	1	1	0	1
1	1	1	1	0	0	0

Figure 2.9: Truth tables of NAND, NOR. XOR Logic Gates.

2.12 Numerical modeling methods

There are many numerical methods for solving the Maxwell equations proposed in Chapter 1. These methods include plane wave method (PWE), finite-difference time-domain method (FDTD), transfer matrices, diffraction matrices, strong correlations and development of self-modes. Among these methods, the PWE and FDTD methods are the most widely used compared to those obtained by computation.

2.12.1 FDTD Method

The FDTD method is currently one of the most widely used methods in electromagnetism. the first algorithm was proposed by Yee in 1966. the method is particularly useful for determining the spectral response of a system that need not be periodic, and for calculating field distributions in finite-dimensional structures. FDTD can be used not only to calculate band diagrams, but also to simulate the time evolution of the electromagnetic field in photonic crystals, providing information on many other quantities such as the Pointing vector or stored electromagnetic energy. It consists in approximating the spatial and temporal point-wise derivatives that appear in Maxwell's equations with centered finite differences [37].

2.12.2 PWE

The plane wave method (PWE) refers to a computational technique in electromagnetism that solves Maxwell's equations by formulating eigenvalue problems from the equations. This approach is popular in the photonic crystal community as a means of solving the band structure (dispersion relation) of a specific photonic crystal geometry. PWE goes back to analytical formulations that can be used to calculate modal solutions to Maxwell's equations on inhomogeneous or periodic geometry [38].

2.13 Conclusion

In this section, we defined logic gates and explained the relationship between them and photonic crystals. We also got an overview of their seven types (AND NOR OR NOT XOR NAND XNOR), types of logic circuits, some of their advantages and disadvantages and some of the calculation methods we will use in the course of our work with an overview of numerical methods FDTD and PWE. the concepts of different photonic crystal logic gates and all-optical logic gates based on photonic crystals are explained.

Chapter 3

Design and analysis of PhC-based NOT, AND, OR, NAND and XOR logic gates using the interference effect.

Contents

3.1 Introduction

Logic gates serve as fundamental building blocks in electronic devices and integrated circuits, playing a crucial role in processing and manipulating digital signals. They are essential components in computer systems, enabling logical operations such as AND, OR, and NOT, which form the basis of computational tasks. Moreover, logic gates are indispensable in telecommunications, where they facilitate data routing, signal modulation, and error correction, ensuring efficient transmission of information across networks. In this chapter, we delve into the exploration of a novel approach to logic gate design, leveraging a Y-shaped structure integrated with a reference signal. By harnessing the concept of interference, we aim to optimize the functionality of this design across a spectrum of logic gates. Utilizing computational modeling techniques such as Plane Wave Expansion (PWE) and Finite-Difference Time-Domain (FDTD), we delve into the intricacies of wave propagation within this innovative architecture. Our objective is to develop a unified design capable of accommodating various logic gates while maintaining a compact footprint. Through meticulous experimentation and analysis, we seek to achieve superior response time results within the confines of a smaller structural footprint, thereby pushing the boundaries of optical logic gate design and integration.

3.2 Description of the structure studied

The structure consists of an array of size 15× 15rods of Si material with having a refractive index of value 3.46 and radius of value 0.2a, where 'a' is named as lattice constant and have value of 600 nm shown in 3.1 and table 3.6.

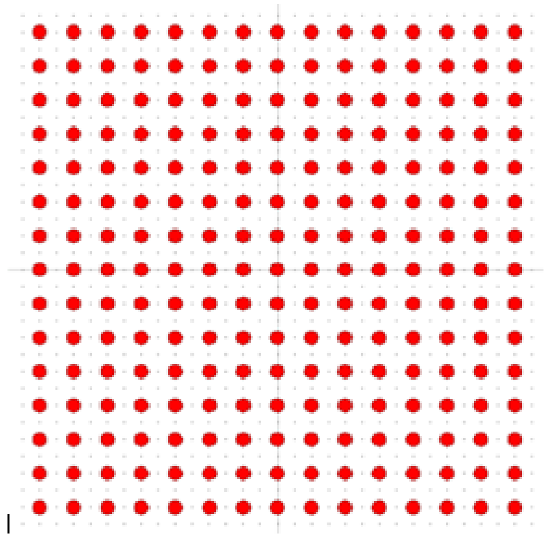


Figure 3.1: 2D square structure with silicon rods .

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

Table 3.1: The structure proposed for the all gates

3.3 Calculation of band gap

The Photonic Band Gaps (PBGs) for waveguide are determined through the PWE method. The PBG illustrated in Figure 3.2 delineates these band gaps. As depicted in the table 3.6 , there are two bands for TE modes, of which the broader spectrum is selected, falling within the communication window. This band encompasses a wavelength range from 1440 nm to 2120 nm,we have chosen 1550nm for our design, equivalent to 0.282568 (a/λ/) to 0.416924 (a/λ/). At these wavelengths, light is reflected back through the Photonic Crystals (PhCs) in figure 3.2.

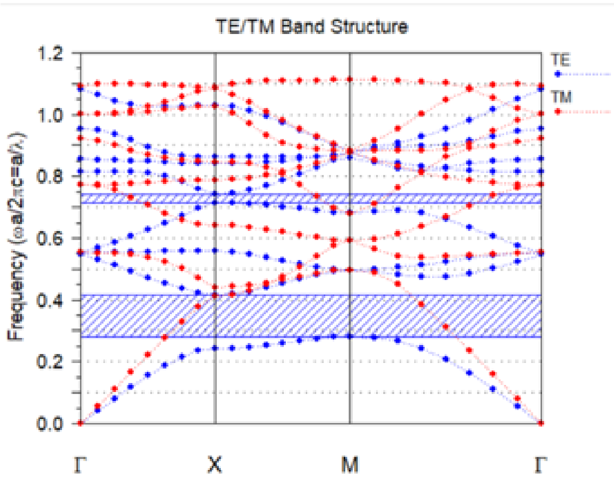


Figure 3.2: Photonic band gap in TE and TM polarizations, in the photonic crystal structure and the dielectric rods radius are 1550 nm.

3.4 Line defect in photonic crystals

Line defect is a very important part of building a structure knowing that each photonic crystal design can be different than the other and what makes it basically different is the line defect, it's basically created by removing or modifying a row or column of dielectric material or by introducing a different material along a line within the photonic crystal this breaks the periodicity along that line while maintaining it in the perpendicular directions.

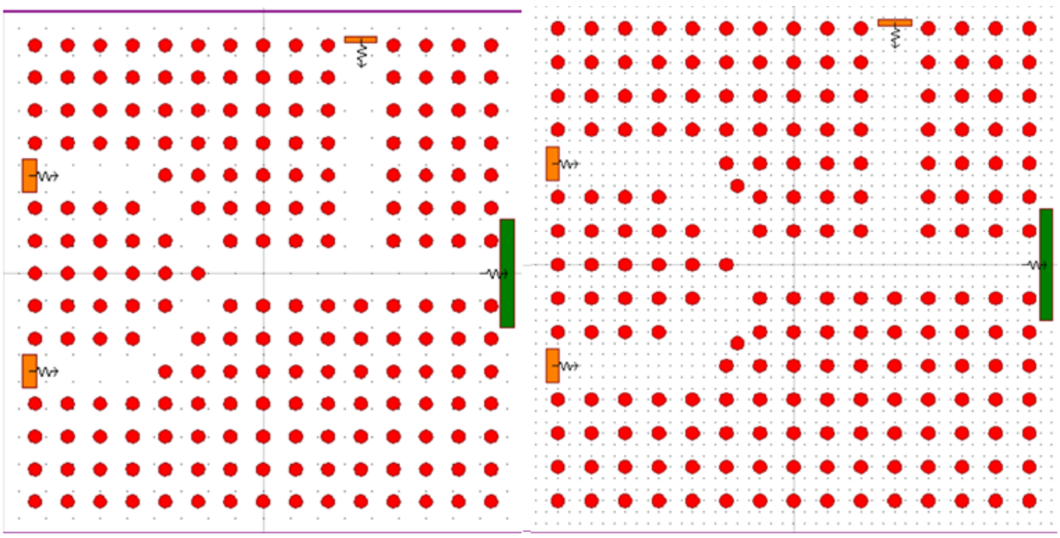


Figure 3.3: The structure of all logic gates.

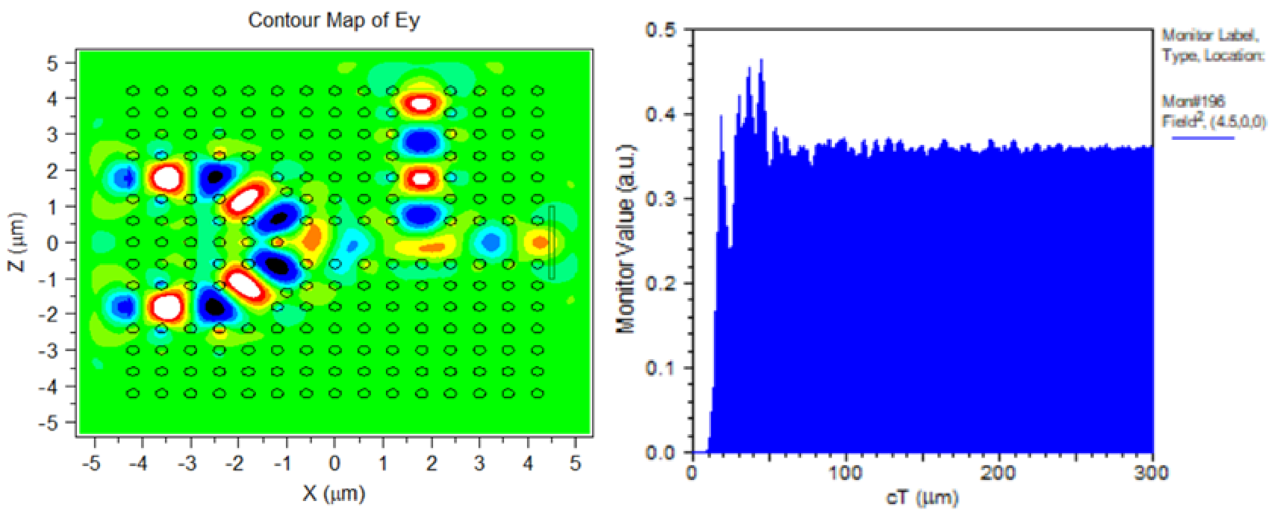


Figure 3.4: Results of the Pre-optimization design configuration.

3.5 Design and operating principle

In Figure 3.3, it is evident that without addressing the defaults and repositioning some rods into a specific configuration, the waveguide will not be able to reach the output effectively, thereby failing to provide the desired results. PhC Controls the spontaneous emission in the lattice.Our proposed design features a combination Y and T-shape common structure through which we execute logical operations such as XOR, NOT, OR, and NAND. Concept interference is employed within this structure to facilitate these logical operations. The combination Y and T-shape is common platform for AND, OR and XOR gates Design is based on the principle of interference. There are four port two inputs, one reference and one output port. Interference can be done in a constructive way which means if the light is coming out of two or out of the three inputs the output will indicate light intensity is obtained representing a low logic function (Logic 1).while destructive interference yields low light intensity, indicative of a high logic function (Logic 0).The input signals, modeled as Gaussian signals, are launched at the input ports, with one input serving as a reference input for the logic NOT gate, as NOT is a single-input function. When no signal is launched, the reference input assumes significance and is subjected to a 180-degree phase shift. To assess the performance of the logic gates, a parameter known as the contrast ratio is defined. This ratio is computed as the average power at the output port for a high logic function divided by the average power for a low logic function. Mathematically, it is expressed as a formula.3.1

$$\mathbf{C} = 10log\frac{\text{P1}}{\text{P0}} \tag{3.1}$$

Where, P1 and P0 are output average for high and low intensity at output port. It is measured in dB always

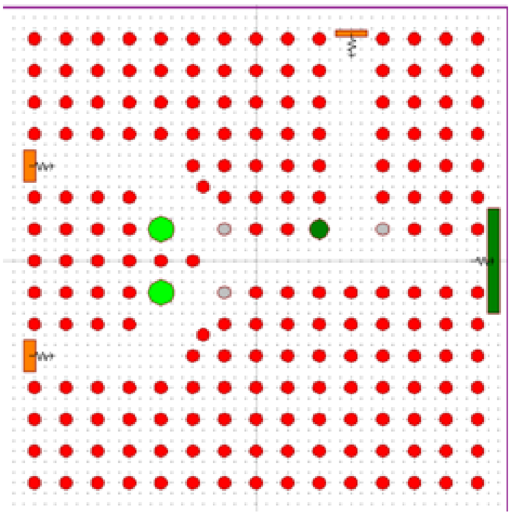


Figure 3.5: The structure proposed for all optical logic gates .

As it's shown in the 3.5 that it is a combination Y and T-shape waveguide created in 2D PhC in Cubic lattice There is a disparity in length. In our proposed design for Y-shape structure there's four waveguides that has been created an A,B and reference ports are considered as inputs ports as it's shown in the 3.5. On the right side of the structure it has been placed the Y port which will indicated the output signal. We managed to create different types of defects in the structure for more flexibility. these defects are places in different rangesin the structure.

3.6 The optimization

3.6.1 Optimizing the reference input

The proposed structure for optical logic gates has been optimized and simulated using the Finite-Difference Time-Domain (FDTD) method. A perfectly matched layer (PML) was applied to meet the Courant condition requirements. Continuous wave (CW) signals with power were used to excite the input ports A, B. The reference signal was utilized to optimize the logic output for all combinations of logic gates.
This structure is design to be applied on all logic gates AND,OR,XOR,NAND, and NOT. In order to achieve optimal functionality, meticulous attention was directed towards the design. The optimization process commenced with refining the REFERENCE input. Upon launching, as depicted in Figure 3.6, it became evident that the waveguide had deviated towards the left direction, consequently diminishing the monitors detection capability due to insufficient light power. Subsequently, a strategic decision was made to install a grey-colored rod on the right side to address this issue. However, even following the implementation of the glass rod, Figure 3.6,below reveals that a significant portion of the light continues to veer away from the monitor. To counter this, measures were taken to enhance light reflection and maintain its trajectory towards the monitor. This involved increasing the size of the green-dyed rod on the left by 0.3*a, effectively preventing light from deviating, as demonstrated in Figure 3.2.

In the figure 3.7 below, we can observe that the rods RJ1 and RJ3 were selected based on the graphical analysis, indicating that they reach their peaks at specific moments. Specifically, RJ1 peaks at 0.3*a, while RJ3 peaks at Radius*2. These parameters were crucial in achieving the desired results, ensuring that the reference signal does not drift excessively and that both input A and input B remain on their designated paths. This careful selection and tuning of RJ1 and RJ3 were instrumental in optimizing the system's performance and maintaining the intended signal flow.

3.6.2 Optimizing the A and B inputs

To optimize the two inputs, we initially focused on refining one input before applying the adjustments to the other. In this particular case, our optimization process commenced with input A. As illustrated in Figure 3.8(a), the majority of light was consistently reflected, prompting us to strategically reposition certain rods both vertically and horizontally. This realignment facilitated the unimpeded passage of light through the designated pathways. However, as depicted in Figure 3.8(b), despite the corrective measures taken to enable unrestricted light flow, a recurring issue persisted—light intermittently deviated backward or diverted into the path intended for input B. To mitigate this unforeseen occurrence, we made a crucial alteration: substituting the previously grey-dyed rod with a transparent glass rod, thereby permitting light to proceed towards the monitor's direction unimpeded. To further ensure minimal loss of light transmission, the rod, originally painted light green, was enlarged to twice its original radius. These meticulous adjustments were instrumental in optimizing the functionality of both inputs, ensuring efficient and uninterrupted light propagation within the system.

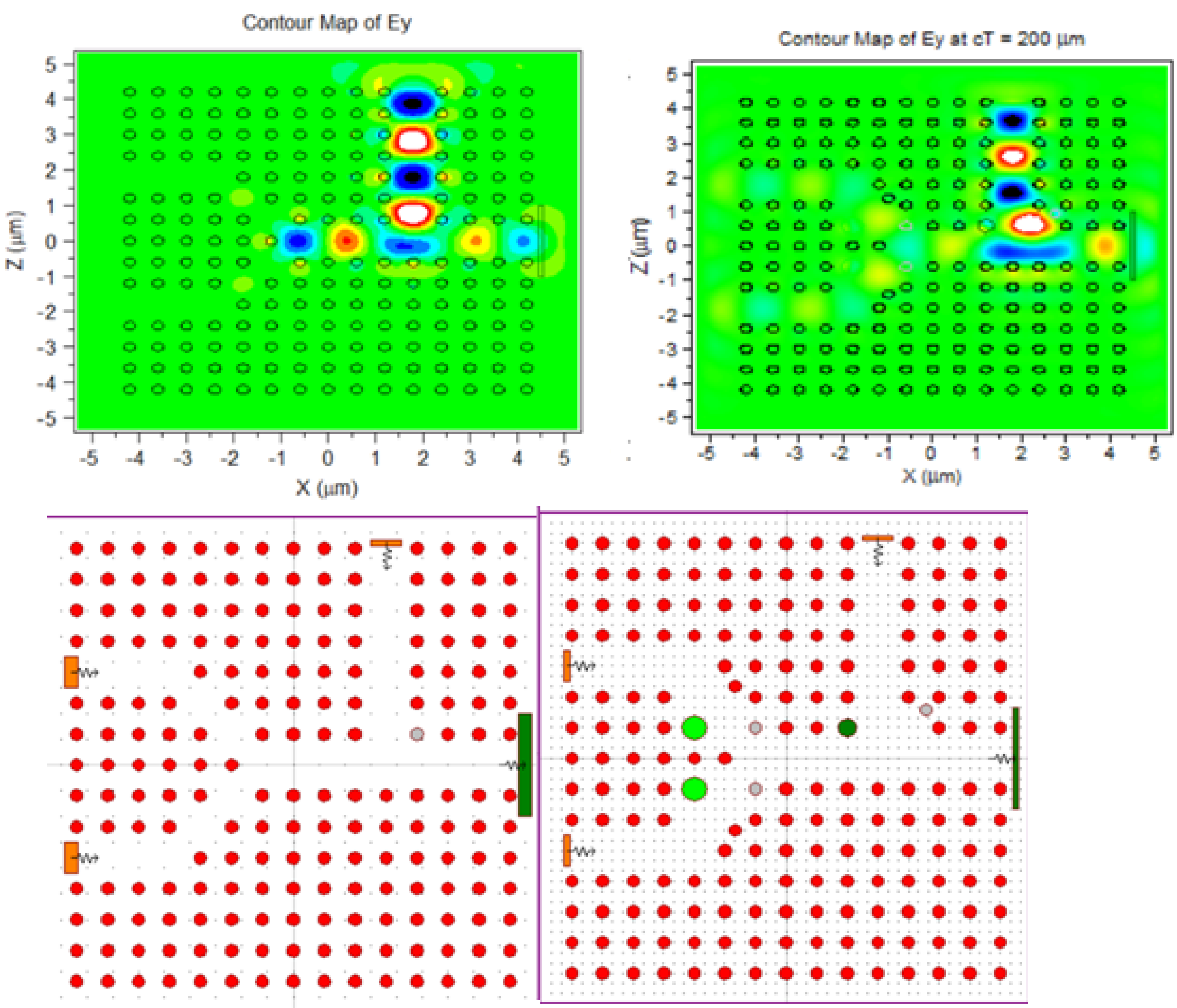
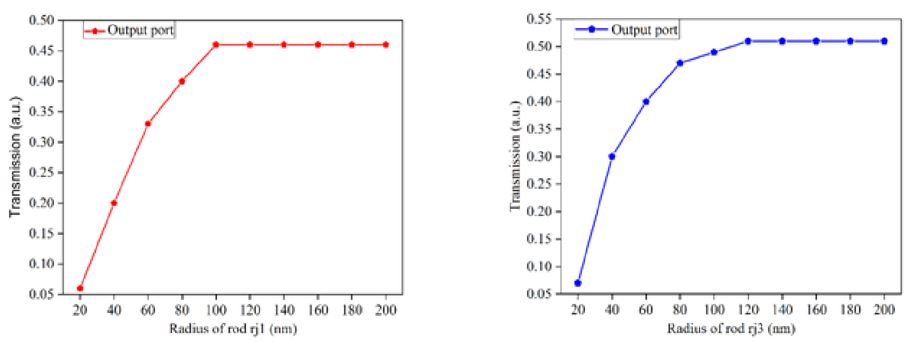


Figure 3.6: Optimizing the Reference input



(A) (B)

Figure 3.7: (A)Effect of radius of rod RJ1 and (B) Effect of radius of rod RJ3

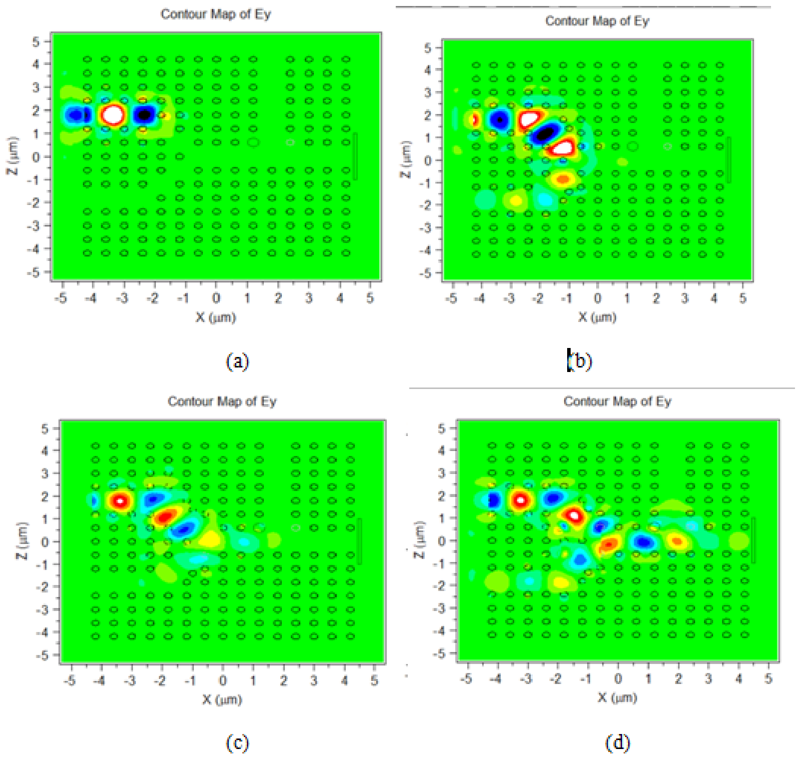


Figure 3.8: The structure represents the ultimate iteration of our all-logic gate design.

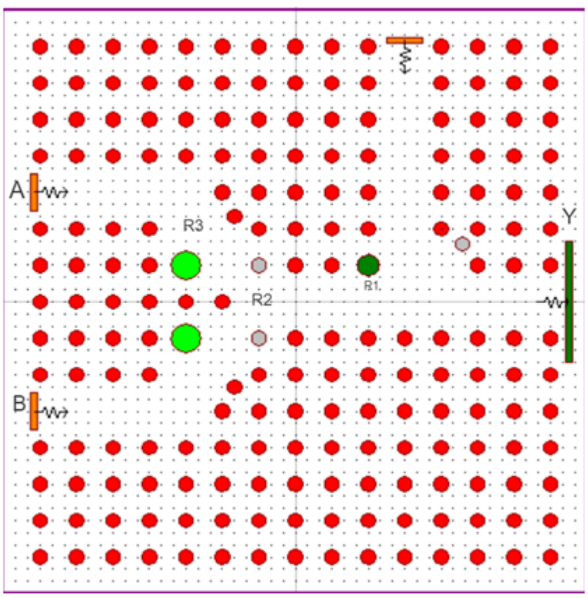


Figure 3.9: final design for our structure .

3.7 Results and discussions

3.7.1 AND gate

In all the logic gates we will introduce and work with, the concept of interference will be central. As previously explained, the operation of these gates relies on the principles of constructive and destructive interference. Specifically, in our design, input A will be launched at a 0-degree phase, while the reference signal will be launched at a 180-degree phase. This 180-degree phase difference will result in destructive interference, leading to low light intensity at output port Y. This low light intensity corresponds to a low logic level. Similarly, for input B, the same process will be applied: input B will be launched at a 0-degree phase, and the reference signal will be at a 180-degree phase. This phase difference will again result in destructive interference, producing a low light intensity at output port Y, defining a low logic level. Conversely, for achieving high logic levels through constructive interference, inputs A and B, along with the reference signal, will all be launched simultaneously at the same phase. In the case of an AND gate, this phase will be 0 degrees. Constructive interference under these conditions results in high light intensity at output port Y, which corresponds to a high logic level. By utilizing these principles of interference, our logic gates will effectively perform the desired logical operations, with low and high light intensities at the output port indicating low and high logic levels, respectively.

To effectively explain the results, we adopted the method illustrated in the figure 3.14 below. According to this method, results exceeding 0.45 are assigned a logic of 1, while results below 0.45 are assigned a logic of 0.

3.7.1.1 Summary on performance analysis of AND Gate

The destructive interference scenario requires one of the inputs, either A or B, to be launched with a 0-degree phase while the reference signal is launched with a 180-degree phase. This phase difference causes the light waves to cancel each other out, leading to a significant reduction in light intensity at the output port Y. The low intensity, typically measured as a fraction of the initial signal, signifies a low logic level (logic 0) figure 3.10. In the constructive interference scenario, both inputs A and B, as well as the reference signal, are launched with a 0-degree phase. This alignment causes the light waves to reinforce each other, resulting in a high light intensity at the output port Y. The increased intensity signifies a high logic level (logic 1), confirming the successful operation of the AND gate when both inputs are active in the figure 3.12. The figures 3.10 and 3.12and3.13 accompanying these results illustrate the distinct field distributions for both constructive and destructive interferences. For constructive interference, the light path is clear and intense, while for destructive interference, the light is effectively minimized or redirected, showcasing the precise control over light propagation within the photonic crystal structure.

3.7.1.2 Calculation of contrast ratio

For this logic gate, the contrast ratio can also be determined by comparing the average power at the output port when the gate is operating in a high logic state to the average power when it is in a low logic state.
For 10% of output CT= 10µm
T1= (10/ 3×102) = 0,0333Ps

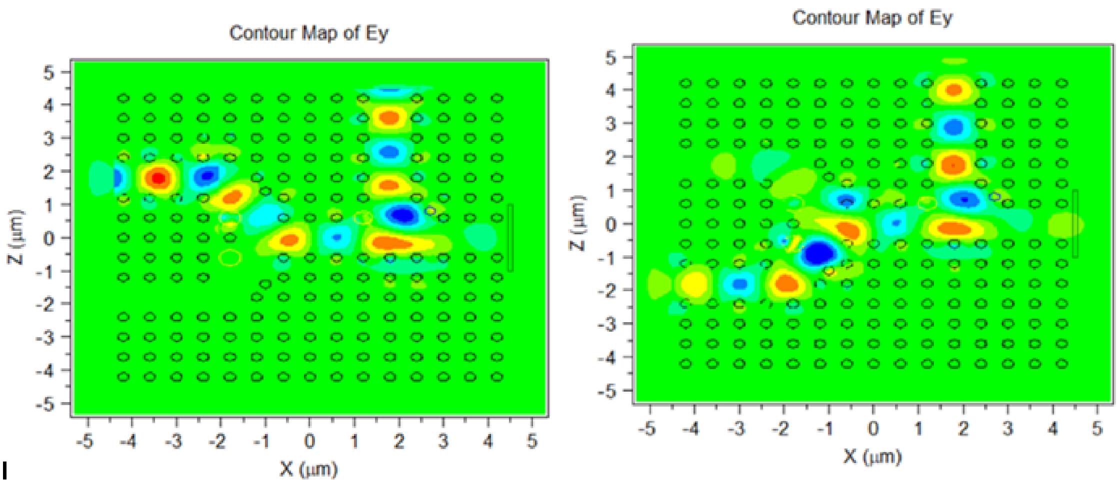


Figure 3.10: Optical Field Distribution of AND Gate for input A=1 or B=1 (0 degree phase) with reference 180 degree phase .

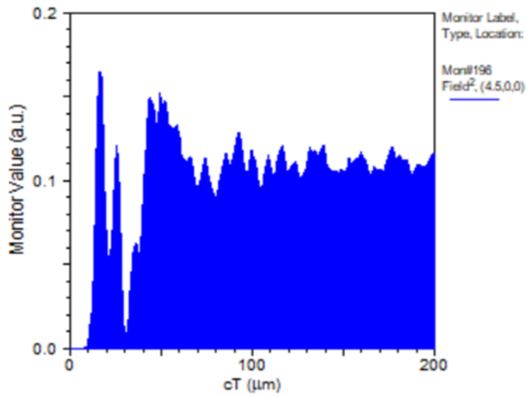


Figure 3.11: Output transmission AND Gate for input A=1 or B=1 (0 degree phase) with reference 180 degree phase .

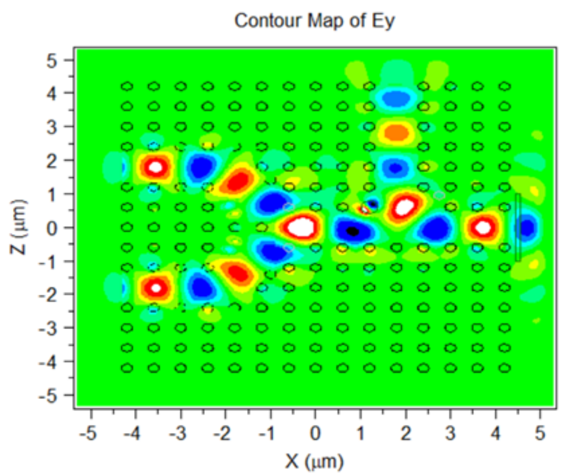


Figure 3.12: Optical Field Distribution of AND Gate for input A=1, B=1 with reference 180 degree phase .

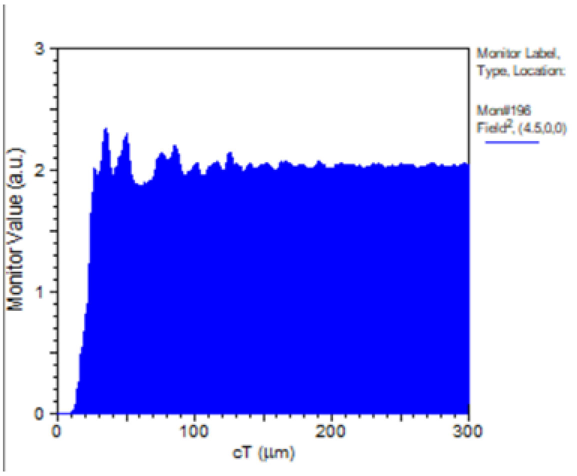


Figure 3.13: Output transmission AND Gate for input A=1; B=1 0 degree phase with reference (0 degree phase).

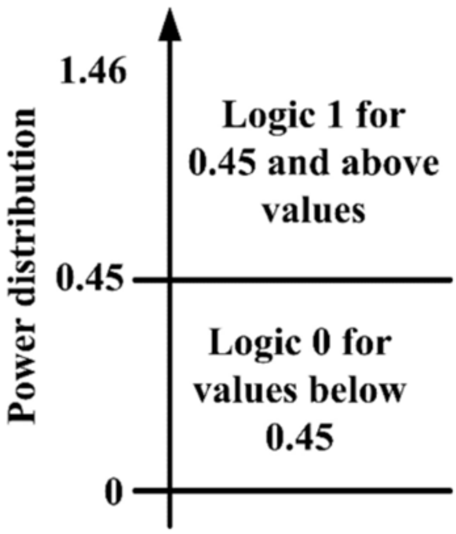


Figure 3.14: Power sharing of “logic 0” and “logic 1” levels.

A (phase =0°)	B (phase =0°)	Reference (phase)	Logic Output	Output Y
0	0	0	0	0
0	1	1(180°)	0	0.105
1	0	1(180°)	0	0.105
1	1	1 (0 °)	1	2.05

Table 3.2: Possible input combinations, required phase values of AND logic gates with output logic value

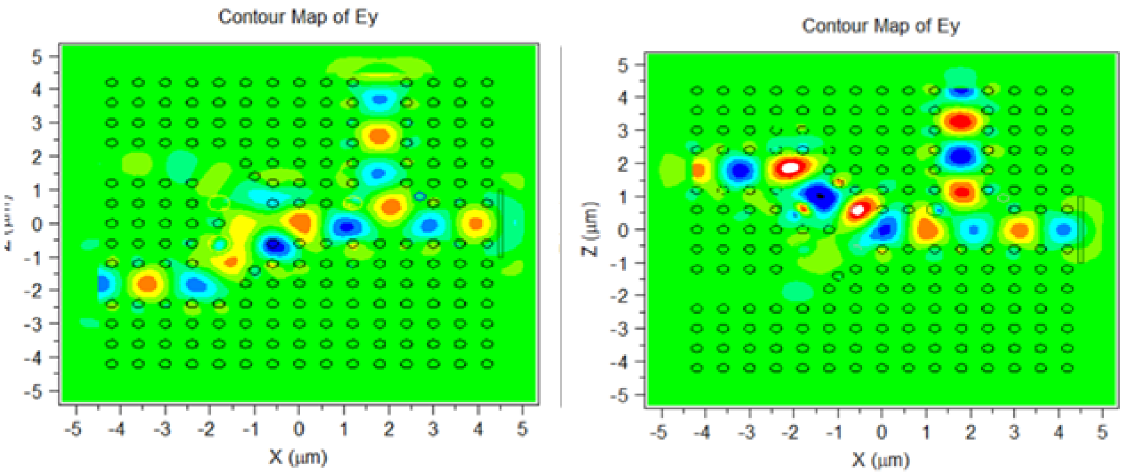


Figure 3.15: Optical Field Distribution of OR Gate for A=0, B=1 and A=1, B=0 with R =1.

For 90% of output CT =28μm
T2=(28/ 3×102) = 0,0933Ps
Response time= 4×(T2 - T1)= 0,24Ps
Extinction ratio= 10 log10(P1/P0)
10 log (0.74 / 0.105) = 12,90564 db

3.7.2 OR gate

For the OR function, both inputs A and B, along with the reference port, will be launched at a 0-degree phase. This synchronization results in constructive interference, causing the output port Y to receive high light intensity. This high light intensity corresponds to a high-level logic state.

3.7.2.1 Summary on performance analysis of OR gate

The figure3.15 illustrates the field distribution when a light signal is launched at either port B or port A, with the reference being launched in both cases. In this combination of Y and T-shape structure, some of the light will be absorbed by rods or oriented in the opposite direction, while the remaining light will be detected by the monitor at output Y. Since one of the inputs is powered at 1 and shares the same phase degree with the reference, this

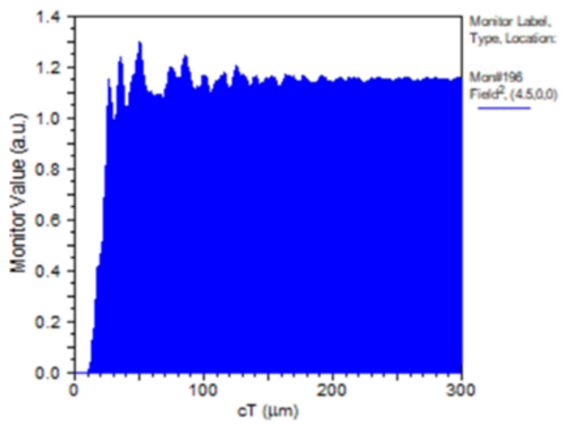


Figure 3.16: Output transmission for OR logic gate for input A=0, B=1 and A=1, B=0 With R=1.

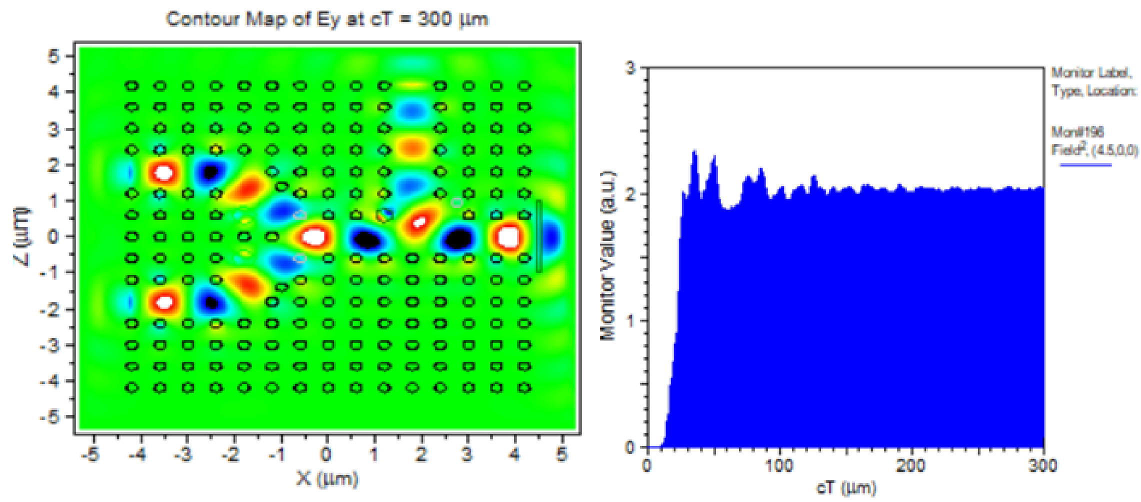


Figure 3.17: Field distribution and output transmission for OR gate for input A = 1 , B = 1.

A (phase =0°)	B (phase =0°)	Reference (phase = 0°)	Logic Output	Output Y
0	0	0	0	0
0	1	1(0 °)	1	1.15
1	0	1 (0°)	0	1.15
1	1	1 (0°)	1	2.05

Table 3.3: Possible input combinations, required phase values of ORlogic gates with output logic value

results in constructive interference, leading to high light intensity. As shown in3.17, the signal light reaches an intensity of 1.15, which is considered a logic level of 1. Similarly, when all inputs A, B, and the reference are launched with the same exact phase degree, the resulting light intensity reaches 2.1. This indicates that constructive interference occurs once again, leading to a high light intensity. Consequently, this high light intensity corresponds to a logic level of 1.

3.7.2.2 Calculation of contrast ratio

For 10% of output CT= 13µm
T1= (13/ 3 ×102) = 0,04333Ps
For 90% of output CT =28µm
T2=(28/ 3×102) = 0,0933Ps
Response time= 4×(T2 - T1) = 0,2Ps
Extinction ratio = 10 log10(P1/P0)
10 log (1.15 / 0) =/

3.7.3 XOR gate

As mentioned earlier, this structure involves three inputs: A, B, and a reference. Essentially, the XOR function operates as the reverse of the OR function. To accomplish this, input A or B needs to be launched at a 0-degree phase along with the reference, which is also launched at a 0-degree phase. Subsequently, to achieve the XOR function, all inputs (A, B, and the reference) are launched simultaneously. Inputs A and B are launched at a (0-degree phase), while the reference is launched at a 180-degree phase, resulting in destructive interference. This destructive interference leads to low light intensity at the output, indicating a low-level logic state.

3.7.3.1 Summary on performance analysis of XOR gate

In the XOR gate, inputs A and B are launched and transferred through the combination T and Y-shape structure, passing the reference signal at the Y-junction, resulting in a logic level of 1 at the output. The XOR logic gate operates oppositely to the OR gate. In one of the cases, to achieve the opposite result of OR inputs A and B are fixed at a 0-degree phase, while the reference is changed to a 180-degree phase. This configuration causes

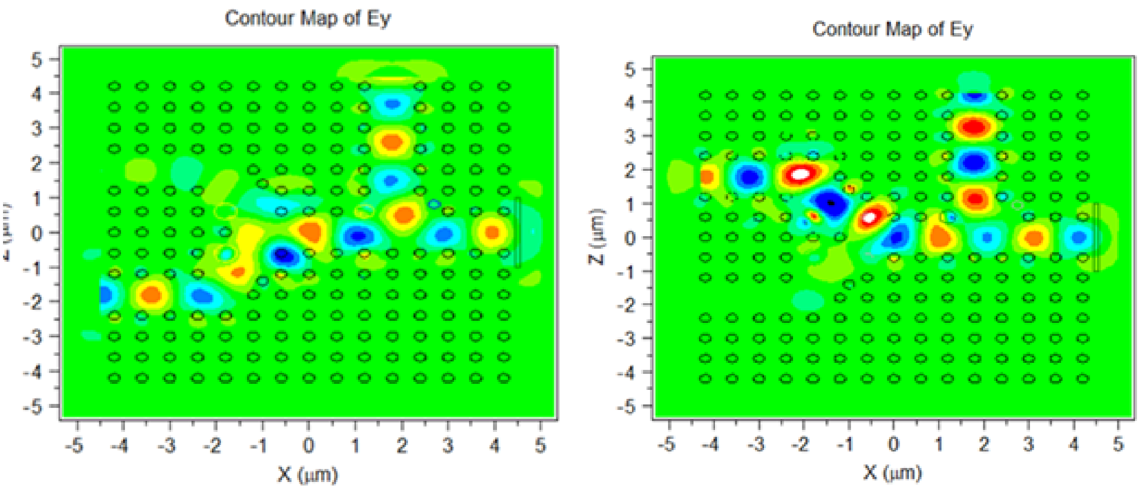


Figure 3.18: Optical field distribution of XOR gate for input A=0 ,B=1 and A=1 , B=0 R= (0 degree phase) .

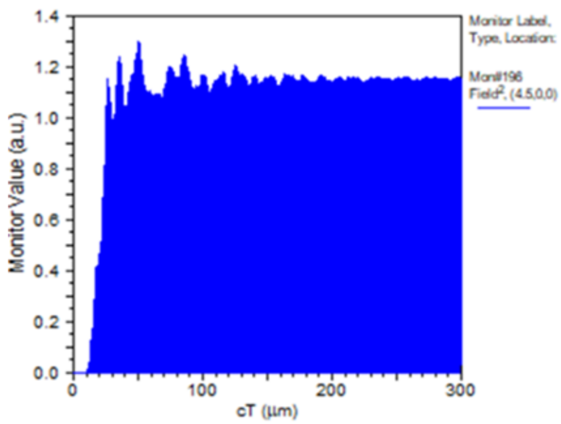


Figure 3.19: Output transmission of XOR gate for input A=0, B=1 and A=1, B=0 with R=0 phase .

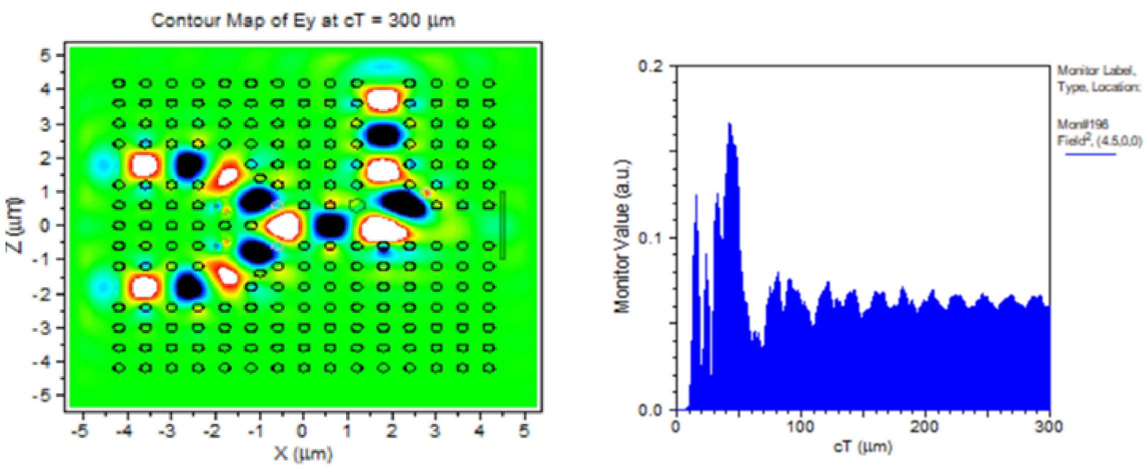


Figure 3.20: Field distribution and output transmission for XOR gate for input A = 1 , B = 1 and R=180 phase.

A (phase =0°)	B (phase =0°)	Reference (phase)	Logic Output	Output Y
0	0	0	0	0
0	1	1 (0°)	1	1.15
1	0	1 (0°)	0	1.15
1	1	1 (180 °)	1	0.06

Table 3.4: Possible input combinations, required phase values of XOR logic gates with output logic value

destructive interference, leading to a low light intensity of 0.06, as shown in Figure 3.18. This low light intensity translates to a low logic output of 0.

3.7.3.2 Calculation of contrast ratio

For 10% of output CT= 10 µm
T1 = (10 / 3 ×102) = 0,03333Ps
For 90% of output CT =28µm
T2 = (28 / 3×102) = 0,0933Ps
Response time= 4 × (T2 - T1) = 0,24Ps
Extinction ratio = 10 log10(P1/P0)
10 log (1.15 / 0.06) =12,825465db

3.7.4 NOT gate

In the NOT function, two inputs are required: one known as the reference input, which will be launched at a 180-degree phase, and another chosen input from A or B, which will be launched at a 0-degree phase with 0 power. The next step involves launching one of the two inputs at 1 power and 0-degree phase, while the reference input remains at 1 power and 180-degree phase. This configuration ensures the correct operation of the NOT function, where the phase difference between the inputs leads to the desired logical inversion.

3.7.5 Summary on performance analysis of NOT gate

As mentioned earlier, the NOT function operates with only two inputs. We start by launching the reference input to create constructive interference, setting the reference input at a 180-degree phase. This phase difference causes the signal to be absorbed by the output Y, resulting in an intensity of 0.46. This intensity is considered high, translating to a high logic level of 1. In another scenario, as shown in figure 3.22, we build destructive interference by launching one of the inputs, A or B, along with the reference at a 180-degree phase. This configuration results in a low intensity of 0.11, which is considered a low logic level of 0.

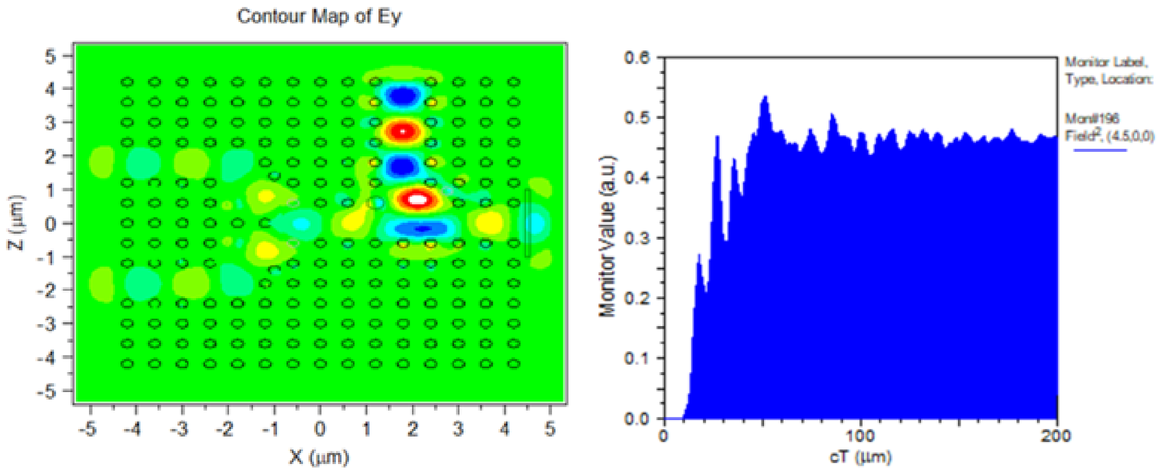


Figure 3.21: Field distribution and output transmission for NOT logic gate for input A = 1.

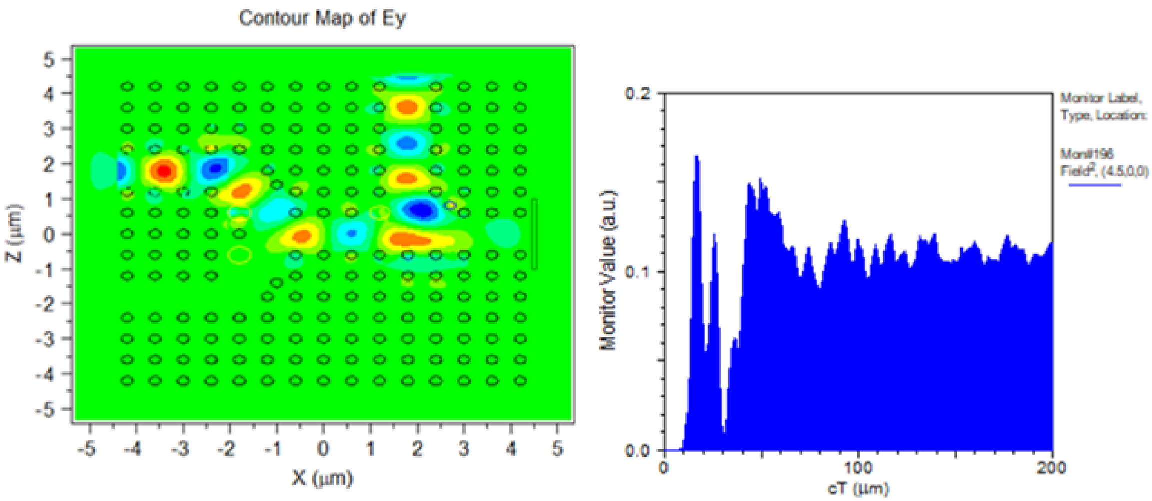


Figure 3.22: Field distribution and output transmission for NOT logic gate for input A = 0.

A= (phase =0°)	Reference	Logic output	Output Y
0	1 (0°)	1	0.46
1	1(180°)	0	0.105

Table 3.5: Possible input combinations, required phase values of NOT logic gates with output logic value

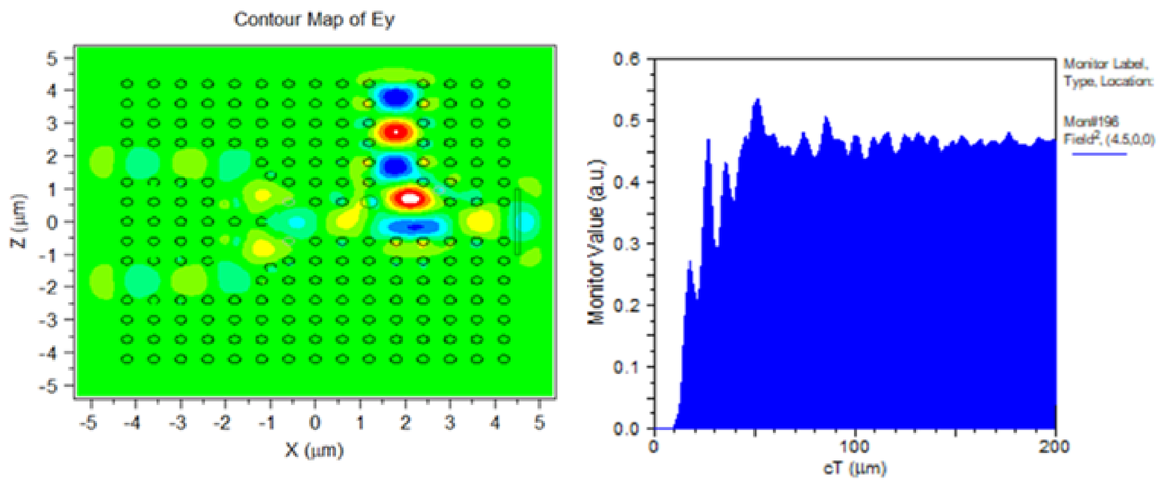


Figure 3.23: Optical field distribution and output transmission of NOR gate for input A=0 , B=0.

3.7.5.1 Calculation of contrast ratio

For 10% of output CT= 9 µm
T1 = (9 / 3 ×102) = 0,03Ps
For 90% of output CT =25µm
T2 = (25 / 3×102) = 0,0833Ps
Response time= 4 × (T2 - T1) = 0,2132Ps
Extinction ratio = 10 log10(P1/P0)
10 log (0.46 / 0.105) =6,415685db

3.7.6 NOR gate

The NOR function will be implemented by first launching the reference input at 1 power with a 180-degree phase, along with input A at 1 power with a 0-degree phase, and input B at 0 power as it's shown in the figures 3.23 . This setup will then be reversed, ensuring each configuration has been tested. Finally, all inputs will be launched simultaneously at 1 power: inputs A and B will be at a 0-degree phase, and the reference will be at a 180-degree phase. This configuration ensures that the correct destructive interference occurs, leading to a low-level logic state at the output, which defines the NOR function.

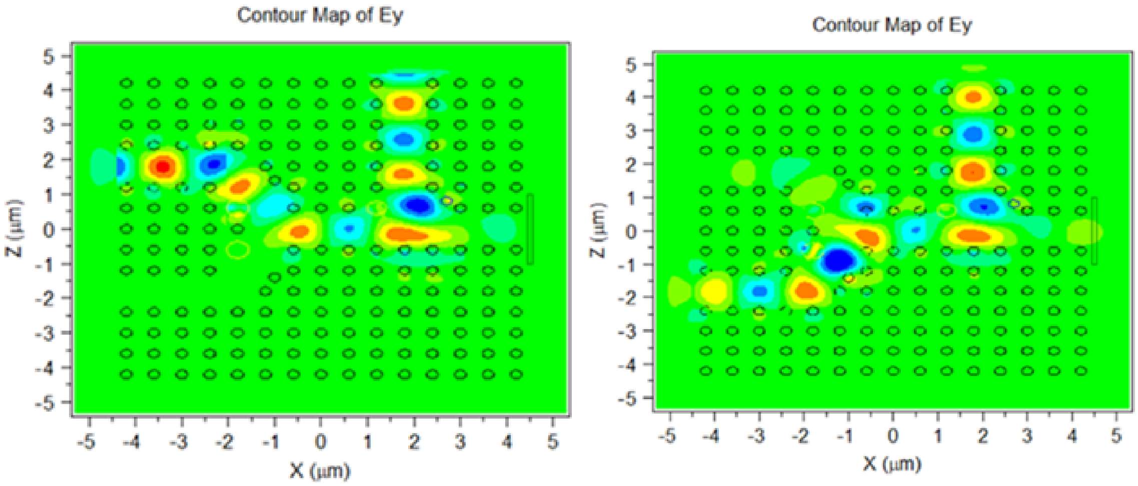


Figure 3.24: Optical field distribution of NOR gate for input A=1 ,B=0 and A=0 ,B=1 .

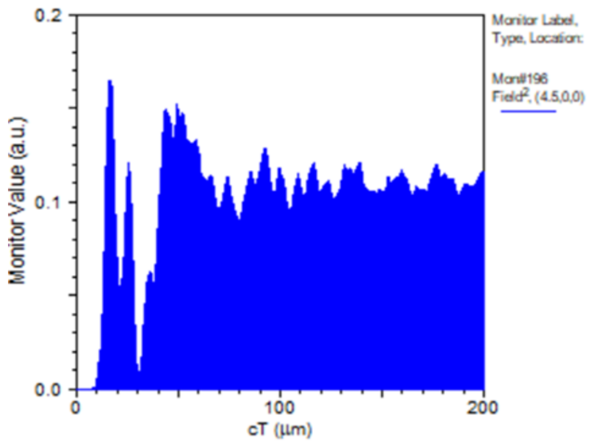


Figure 3.25: Output transmission for NOR gate for input A=1 ,B=0 and A=0 ,B=1 .

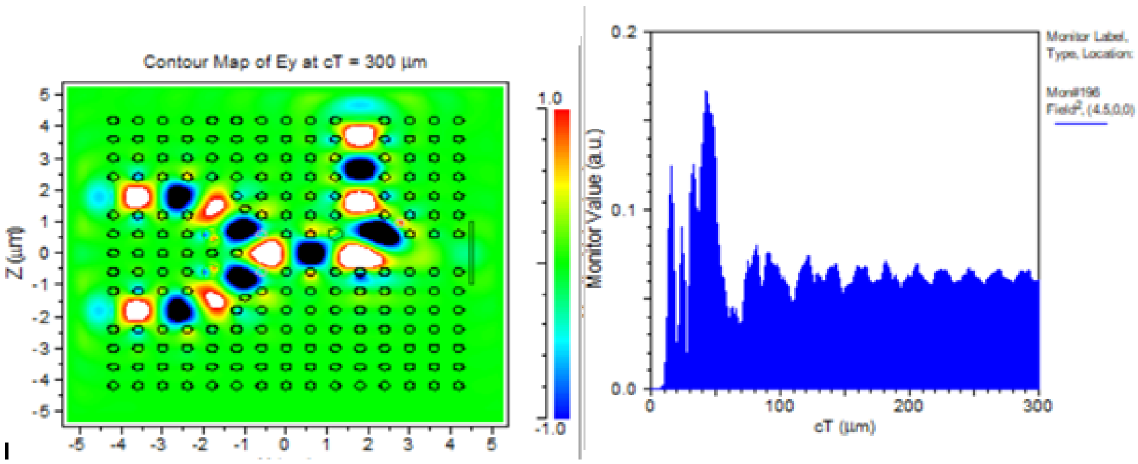


Figure 3.26: Optical field distribution and output transmission for NOR gate for input A=1 ,B=1 .

A (phase =0°)	B (phase =0°)	Reference (phase = 180°)	Logic Output	Output Y
0	0	1 (180°)	1	0.46
0	1	1 (180°)	0	0.105
1	0	1 (180°)	0	0.105
1	1	1 (180 °)	0	0.06

Table 3.6: Possible input combinations, required phase values of NOR logic gates with output logic value

3.7.6.1 Calculation of contrast ratio

For 10% of output CT= 10 µm
T1 = (10 / 3 ×102) = 0,03333Ps
For 90% of output CT =25µm
T2 = (25 / 3×102) = 0,0833Ps
Response time= 4 × (T2 - T1) = 0,2132 Ps
Extinction ratio = 10 log10(P1/P0)
10 log (0.46 / 0.105) = 6,41568db

3.7.7 XNOR gate

The XNOR logic gate operates as the logical inverse of the XOR logic gate, producing an output of "1" if both input values are the same and "0" if the input values differ, as illustrated in figure 3.27. The function of the XNOR logic gate can be described as follows: both input ports are either excited with signals having a phase angle of 0° or are not excited with any signal. Still, the reference signal is launched at the reference port R with a phase angle of 0°, and the output at port Y is logical "1". (ii) When either of the input ports is launched with an input signal having a phase angle of 0° along with the reference signal having a phase angle of 180°, the output at port Y is logical "0". Along with the output values shown in Table 3.7, indicates that the proposed structure is capable of functioning as an XNOR logic gate.

3.7.7.1 Calculation of contrast ratio

For 10% of output CT= 13 µm
T1 = (13 / 3 ×102) = 0,0433Ps
For 90% of output CT =28µm
T2 = (28 / 3×102) = 0,0933Ps
Response time= 4 × (T2 - T1) = 0,2532 Ps
Extinction ratio = 10 log10(P1/P0)
10 log (0.46/ 0.105) = 6,41568db

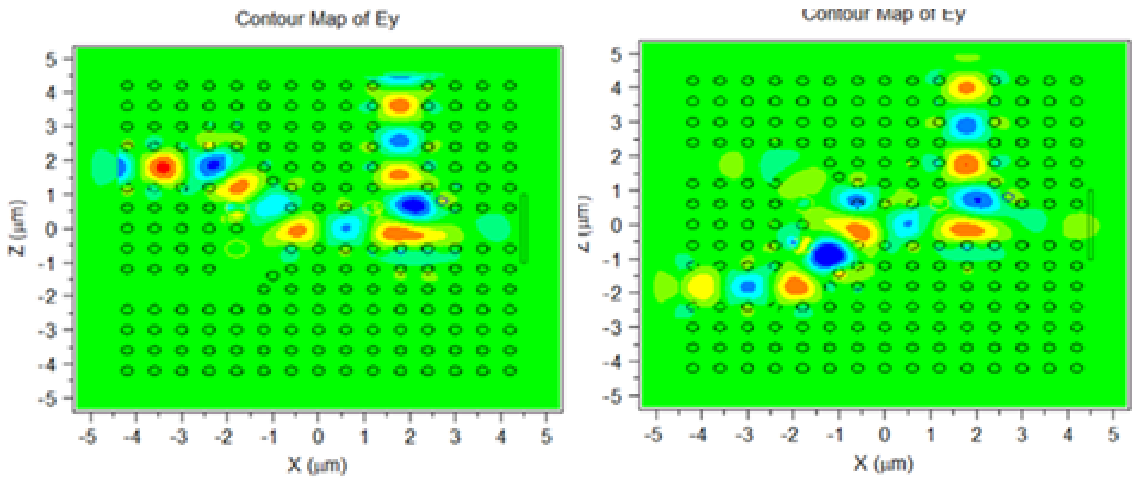


Figure 3.27: Optical field distribution of XNOR gate for input A=1 ,B=0 and A=0 ,B=1 .

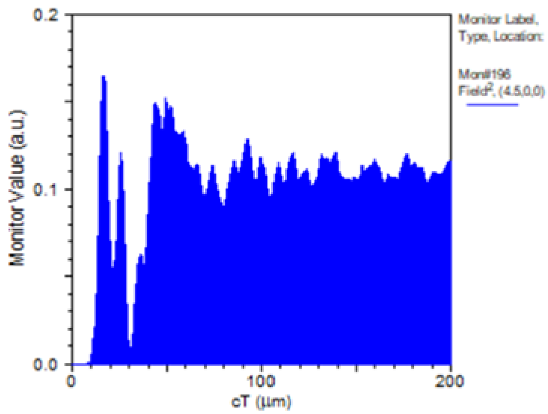


Figure 3.28: Output transmission for XNOR gate for input A=1 ,B=0 and A=0 ,B=1.

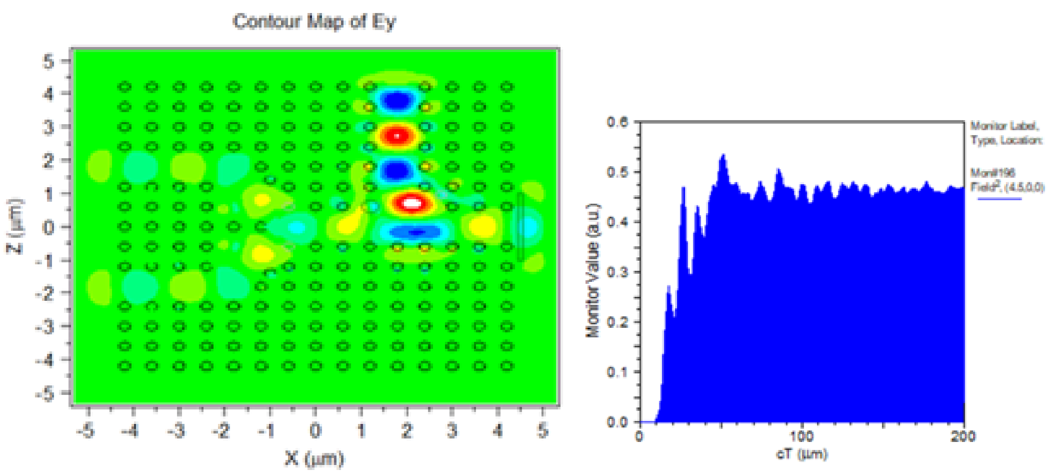


Figure 3.29: Optical field distribution and output transmission for XNOR gate for input A=0 ,B=0 .

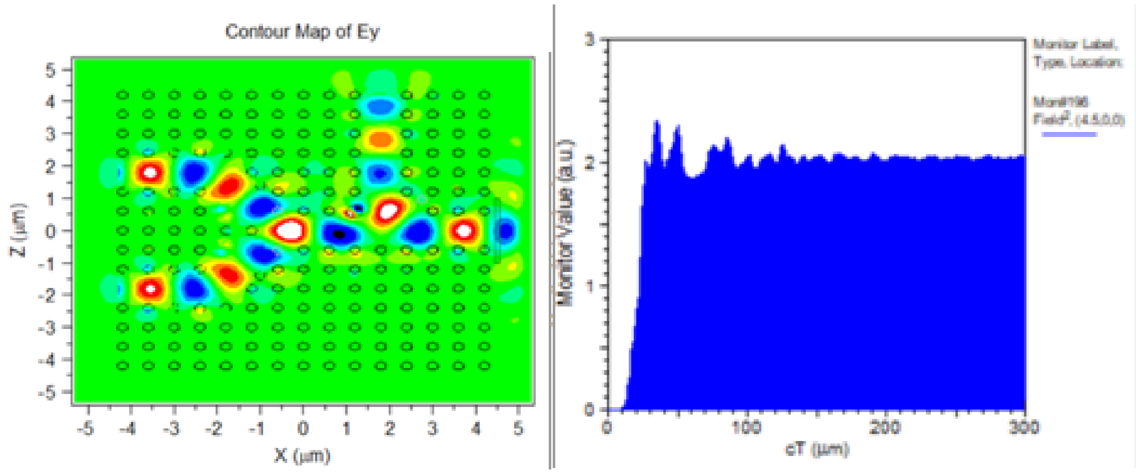


Figure 3.30: Optical field distribution and output transmission fo XNOR gate for input A=1 ,B=1 .

A (phase =0°)	B (phase =0°)	Reference(phase)	Logic Output	Output Y
0	0	1 (180°)	1	0.46
0	1	1 (180°)	0	0.105
1	0	1 (180°)	0	0.105
1	1	1 (0°)	1	2.05

Table 3.7: Possible input combinations, required phase values of XNOR logic gates with output logic value

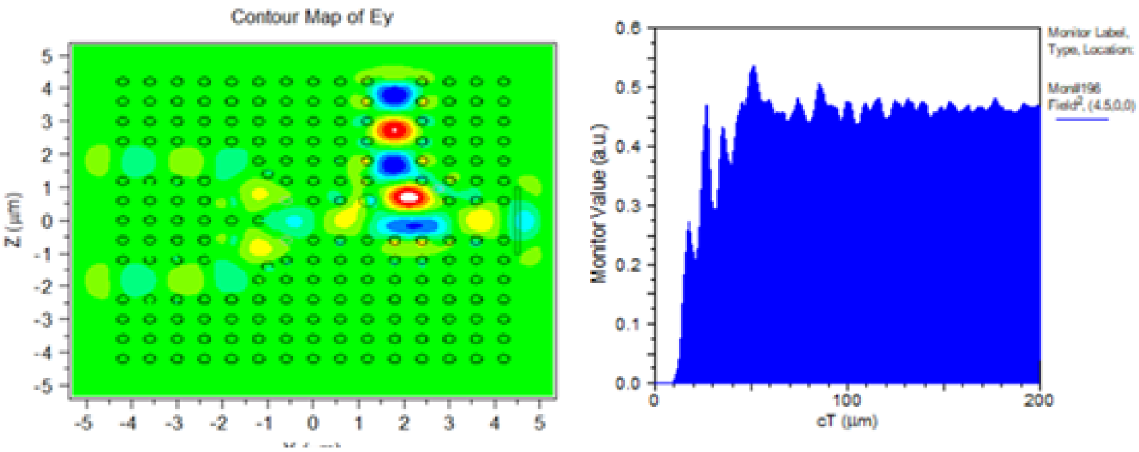


Figure 3.31: Optical field distribution and output transmission for NAND gate for input A=0 , B=0.

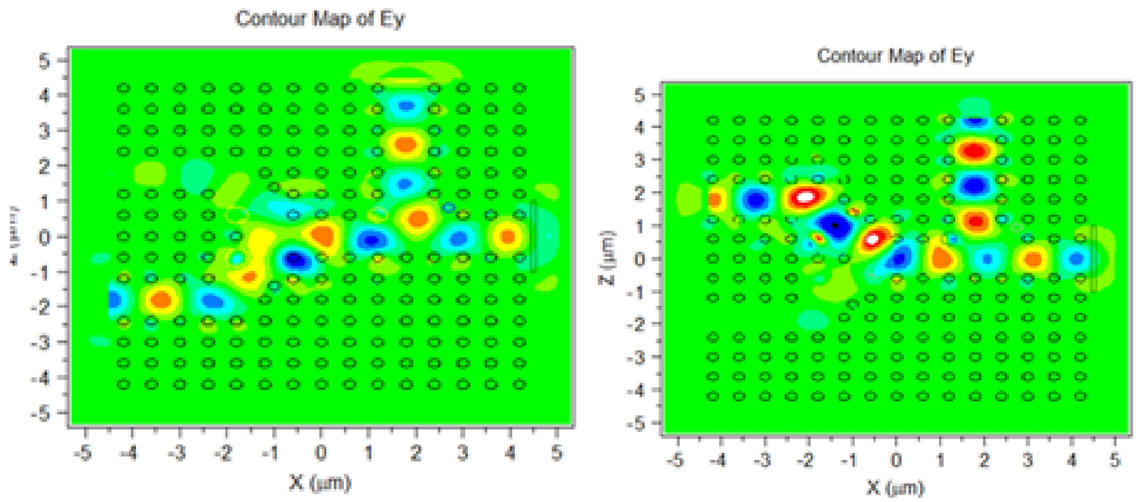


Figure 3.32: Optical field distribution of NAND gate for input A=1 ,B=0 and A=0 ,B=1.

3.7.8 NAND gate

The NAND gate functions as the inverse of the AND gate, meaning its output logic values are the opposite of those produced by an AND gate. Specifically, the NAND gate outputs a logical ’1’ when a light is launched at either one of the two inputs or when no light is launched at both inputs. Conversely, it outputs a logical ’0’ when both input values are launched along with the reference signal as shown in figure 3.31. The operation of the NAND gate is as follows when the reference signal is launched at the reference port R with a phase angle of 0° and no signal is launched at the input ports, or a signal with a phase angle of 0° is launched at either input port A or B, the output port Y registers a logic ’1’. However, when light with a phase angle of 0° is launched at both input ports A and B and the reference port R is launched with a signal having a phase angle of 180°, the output port Y registers a logic ’0’.

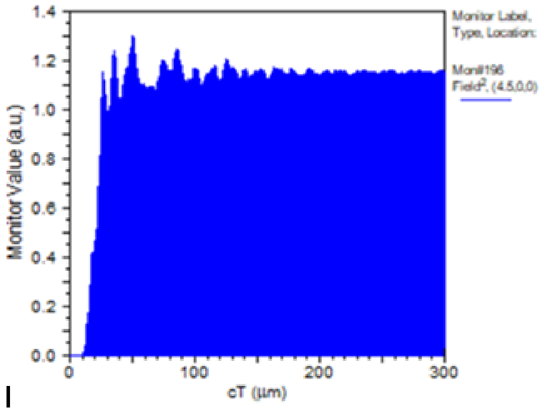


Figure 3.33: Output transmission for NAND gate for input A=1 ,B=0 and A=0 ,B=1.

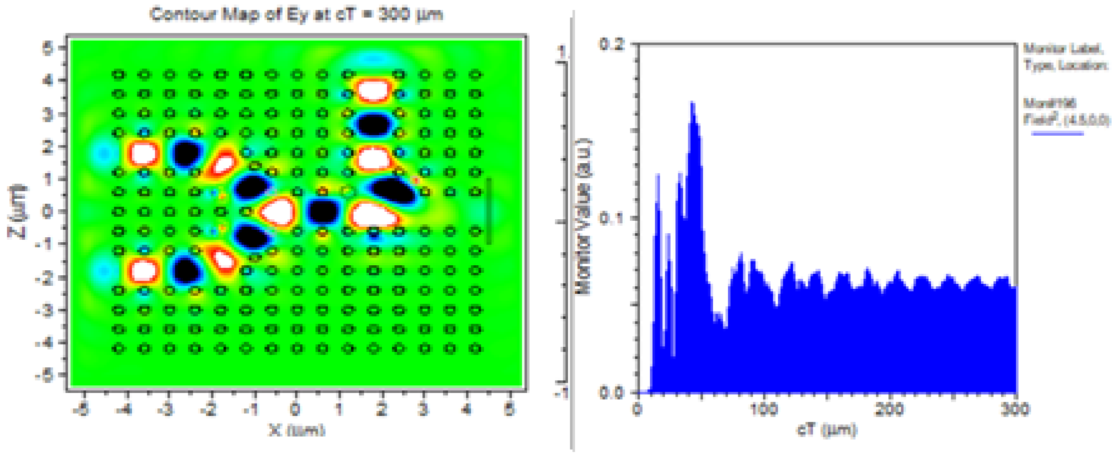


Figure 3.34: Optical field distribution and output transmission for NAND gate for input A=1, B=1.

A (phase =0°)	B (phase =0°)	Reference (phase)	Logic Output	Output Y
0	0	1(0 °)	1	0.46
0	1	1(0 °)	1	1.15
1	0	1(0 °)	1	1.15
1	1	1(180 °)	1	0.06

Table 3.8: Possible input combinations, required phase values of NAND logic gates with output logic value

3.7.8.1 Calculation of contrast ratio

For 10% of output CT= 10 μm
T1 = (10 / 3 ×102) = 0,03333Ps
For 90% of output CT =25μm
T2 = (25 / 3×102) = 0,0833Ps
Response time= 4 × (T2 - T1) = 0,2132 Ps
Extinction ratio = 10 log10(P1/P0)
10 log (0.46 / 0.06) = 8,84606db

3.8 Conclusion

This research focuses on the design and analysis of logic gate structures with a combination of T and Y-shaped waveguides and an added reference. The purpose of the reference is to ensure that light consistently reaches the output. This design is intended to function with all logic gates. After optimizing the structure, we achieved results for the following gates: AND, OR, XOR, NOT, NOR, XNOR, and NAND, yielding efficiencies of 2.05, 2.05, 1.15, 0.46, 0.46, 2.05, and 1.15, respectively. These results provided us with an average response time of 0.22465 ps. Table 3.9 presents a comparative analysis of the proposed design with previously published works. Investigations of 2-D photonic crystals (PhCs) were conducted using electronic computational modeling methods such as Plane Wave Expansion (PWE) and Finite-Difference time domain (FDTD). These methods confirmed the existence of a bandgap in the structure and demonstrated the animated flow of light within it. The logic gates based on the 2-D PhCs are designed such that the ratio a/λ for the modeled device operates within the 1450 nm to 2150 nm range, making it highly suitable for most telecommunication applications. Additionally, the designed optical logic devices can be used for cascading, paving the way for future optical memory development.

3.8.1 Comparison between our proposed structure and those studied in previous articles

In work [39], [7], and [40] , a region of 144(μm)2, 85.8, and 54.7(μm)2, respectively, was selected, which is small compared to our work's region of 225(μm)2.
At the NOT, XOR, XNOR, XNOR, and AND gates, a response time of 0.84 ps, 8.33 ps, and

Literature (reference)	Logic devices	Area $(\mu m)^2$	Efficiency (%)	Extinction ratio (dB)	Response time (ps)
[41]	XOR	252	*	19.95	0.466
	NOT	252	*	19.95	0.466
[39]	NOT	144	*	10.79	0.84
[40]	NOT	54.7	*	5.42	1.024
	AND	54.7	*	8.76	1.024
	XOR	54.7	*	8.49	1.024
[42]	NOR	*	*	3.1	*
	XNOR	*	*	7.2	*
	NAND	*	*	7.4	*
	AND	*	*	4.9	*
[43]	NOT	961	0.658	10.21	0.416
	OR	1960	0.89	*	0.128
	AND	304	0.75	6.19	0.24
Proposed work	AND	225	2.05	8.48042	0.24
	OR	225	2.05	*	0.2
	XOR	225	1.15	12.8254	0.24
	NOT	225	0.46	6.41568	0.213
	NOR	225	0.46	6.41568	0.2132
	XNOR	225	2.05	6.41568	0.2532
	NAND	225	1.15	8.8460	0.2132

Table 3.9: Comparison between our structure and those of previous articles

1.024 ps was recorded, respectively, which is longer than our work, which recorded a response time of 0.2 ps.
the results are shown in the table 3.9.

General conclusion

Exploiting photonic crystals to fully process optical signals represents a promising alternative to overcoming the limitations of traditional electronic circuits. The scientific community is actively searching for ways to control light with light using photonic crystals, as this approach holds the potential to revolutionize optical communication and computing. Photonic crystals have emerged as a versatile platform for creating nanoscale optical devices, offering unique properties that traditional materials cannot match. By manipulating the photonic bandgap, these materials can precisely control the propagation of light, enabling the development of highly efficient and compact optical components. In the field of optical communications, photonic crystals are indispensable due to their ability to perform a wide range of optical functions. Their inherent properties allow them to be used in applications such as optical power splitters, optical filters, and couplers. Furthermore, they can facilitate multiple wavelength splitters and wavelength multiplexers, enhancing the capacity and efficiency of optical networks. The ability to integrate these diverse functionalities into a single platform highlights the transformative potential of photonic crystals in advancing optical technologies and addressing the growing demand for high-speed, high-capacity communication systems. Photonic crystals are artificial or natural materials whose refractive index is periodically modified in one or more directions in space. A crystal consists of a periodic arrangement of atoms consisting of a repetition in space of an elementary pattern. It is an artificially engineered photonic material in which the dielectric constant changes periodically. Among its forms is a two-dimensional cyclic structure, which was worked on in this thesis. To ensure compatibility with a wide range of logic gates, our initial focus was on fundamental gates such as AND, NOT, and OR. We opted for a Y-shaped design and incorporated a reference into the waveguide, utilizing a wavelength of 1550 nm and a period of 0.6. This structure operates on the principle of interference, modulating between two phases: 0 degrees and 180 degrees. For the initial gates (AND, OR, NOT), the results were promising. The extinction ratios achieved were 8.48, 0, and 6.41568, respectively, while the response times were 0.24 ps, 0.20 ps, and 0.213 ps, respectively. These encouraging outcomes motivated us to extend our study to additional gates such as XOR, NOR, XNOR, and NAND. The results for the additional logic gates were significant, with the XOR gate achieving an extinction ratio of 12.8254 and a response time of 0.24 ps. The NOR gate demonstrated an impressive extinction ratio of 6.41568 and a response time of 0.2132 ps. Similarly, the XNOR gate yielded an extinction ratio of6.41568 and a response time of 0.2532 ps. Finally, the NAND gate matched the NOR gate with an extinction ratio of 8.8460 and a response time of 0.2132 ps These results culminated in an average response time of 0.22465 ps in a 225μm^2, demonstrating the efficacy of our Y-shaped design and its potential for versatile application across various logic gates. This thorough analysis underscores the viability of our approach, paving the way for future integration in optical computing and telecommunication systems.

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