PLASMONIC WAVEGUIDE BASED ALL OPTICAL LOGIC GATES

A Dissertation submitted in partial fulfillment of the requirement for

the award of degree of

Master of Technology

In

Microwave and Optical Communication Engineering

Submitted by

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(Formerly Delhi College of Engineering)

BAWANA ROAD, DELHI

2015-2017

DECLARATION

I, hereby declare that the work embodied in the dissertation entitled **“PLASMONIC WAVEGUIDE BASED ALL OPTICAL LOGIC GATES”** towards the partial fulfillment of the requirements for the award of degree of **Master of Technology** with specialization in **Microwave and Optical Communication Engineering** is an authentic record of the work carried out under the supervision of **Dr. Yogita Kalra**, Assistant Professor, Applied Physics Department, Delhi Technological University, Delhi.

The matter embodied in this dissertation record has not been submitted by me for the award of any other degree.

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CERTIFICATE

Date: ___________

This is to certify that the work embodied in the thesis entitled **"Plasmonic Waveguide Based All Optical Logic Gates"** submitted by **Sonia** with **Roll no. 2K15/MOC/19** in partial fulfillment for the award of **degree of Master of Technology in MICROWAVE AND OPTICAL COMMUNICATION ENGINEERING,** is an authentic record of student's own work carried out under my supervision.

This work is original research and has not been submitted, in part or full, to any other University or Institute for the award of any degree.

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ACKNOWLEDGEMENT

I am very thankful to **Dr. Yogita Kalra** (Dept. of Assistant Professor, Applied Physics) and all the faculty members of the Dept. of Electronics and Communication Engineering, DTU. They all provided us with immense support and guidance during the project.

I would also like to express gratitude to **Mr. Nishant Shankhwar** (Research Scholar, Delhi Technological University) for providing me continuous support and guidance during this project.

I would also like to express my gratitude to the university for providing us with the laboratories, infrastructure, testing facilities and environment which allowed us to work without any obstructions.

I would also like to appreciate the support provided by our lab assistants, seniors and our peer group who aided us with all the knowledge they had regarding various topics.

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M.Tech (MOC)

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ABSTRACT

Plasmonics is a recent involving very interesting subfield of nanophotonics that plays with the interaction of light with surface plasmons, surface plasmons are the collective charge oscillations that occur at the interface between a metal-dielectric interfaces, such as a metal sheet in air.

Plasmonics fulfill requirement in optical interconnects that are small enough to coexists with nano scale electronic circuits. Nowadays many researchers are try to using plasmonincs in many optical application because in case of plasmonic devices electromagnetic waves can be confined in dimensions much smaller than the wavelength of opertion.

In this thesis, design of plasmonic waveguides based various optical logic gates have been proposed. Various designs of Photonic crystal based optical logic gates have already been envisioned and proposed during the past decade, in which, wavelength of operation is comparable to the geometrical parameters. On the contrary, the proposed structure consists of plasmonic waveguides whose thickness is much smaller than the wavelength of operation.

This may pave the way for large scale integration for the development of all optical circuits for optical computing systems. Moreover, the proposed design is simple and easy to fabricate using techniques like thin-film technology and lithography.

For analysis of plasmonic waveguides, various numerical techniques have been used to reveal the dispersion properties of supported modes. The rest of the thesis deals with the design and analysis of waveguide based all optical plasmonic gates, for which, magnetic field distribution has been obtained for each device. Moreover, by calculating the relative power levels at the input and output ports, the truth tables have been as well.

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CHAPTER-1

INTRODUCTION

1.1 State of art in Electronic Computing

Electronic computing has become most important part in our industry. Electronic computing allow us to pack more and more components onto a single integrated circuits which allows the miniaturisation of the electronics equipments. Small and lightweight devices are now performing complex functions [ref 4]. Today's daily routine lives are heavily dependent on electronics. There are devices which can work by sensing one's finger print, heat and voice command [ref 2]. Such smart devices are presently the hot area of research and development. Modern civilization cannot survive without electronics as they have became basic amenities of the human life.

All these electronics devices are generally based on the semiconductors and involve the use of active (transistors, opamps) and passive devices (resistance, conductance and the inductance). But we can also analyses that these devices will be limited in the future as resistance produces excessive heat in the devices sometimes its burn the wire, and presence of capacitance and inductance causes some delay. Electricity also dissipates high heat and electromagnetic radiation. So our scientists keeping finding the better way to solve these problems. They are finding more ideas so we can reduce these problems. PHOTONICS based devices is one of the solution for this problem because when by photons as a medium instead of the electrons, there are two major advantages [ref 3]:

- It has very high speed.
- It has less heat dissipation in the medium.

That’s why photonics devices are not restricted by the limitation associated with electronic devices. As a result of which computing is now shifting optical regime.

1.2 Need of optical computing

Using light in place of electric current has many advantages. For which we can use the photons as the medium in the devices as photons will replace the limit of electronic computing as photons have the less heat dissipation characteristics and have the higher speed.

In electronic based devices current flow with the speed less than 10 percent of speed of light. But in optical based devices light flows in the material because of which optical based devices are of high performance devices. Optical computing uses light as the medium which is produced by laser diode in instead of electrons. Photons have the higher bandwidth with the comparison of electrons. Already photons based devices have been there and also some optical integrated devices has been manufactured, Photonics based logic gates[ref 4] have been designed which have the less time response than the normal.

Optical computing advantages over the electronic computing:

- Optical computing has high speed with comparison to electronic computing. As optical devices have the light as the medium instead of electric current.
- Optical computing uses the less power consumption with comparison to electronics computing as light has no friction inside the material in optical based devices.
- Optical computing based devices are produce less heat as comparison to electronic computing as electronic basis devices have resistance which is the major source of heat dissipation.
- Conventional computer which are based on electronic devices generally have the rotors and fans which create greater noise but optical computer do not have any fan to create such type of problem. It means optical computing is less noise producing devices.
- With the help of the optical computing we are able to designs laptops etc because it allows chip designing and large scale designing very conveniently.

So we have the need of optical computing to make us more modern. Due to less noise produce reason we use the optical basis devices in the short range communication. Optical fiber technology is now being used for high speed high density data transmission. Different wavelengths of light can travel through a optical fiber without interfering with each other. Optical computing is more secure in case of transmission of ay information as comparison to the electronic computing.

Photons based devices are used because of the less heat produce and high speed. But one of the advancement is plasmonics. By the use of plasmonics we can design the devices which having the smaller dimension in comparison to wavelength use.

1.3 State of the art in optical computing (examples of some basic optical computing devices)

Various optical based devices have been designed. many researchers purposed optical based basic designs. Basic optical devices are which have very bright future:

Optical computers: An optical computer is a computer which does its all computational and function through the photons instead of electron. Optical computer have the feature that it can send data through the use of multiple frequencies. Information is sent on the channel in the form of packets and waves not like the sent through electron beam. This computers are generally of very high speed as no need of conversation is required to changing from binary to optical.

Lenslet's Optical Processor: Lenslet's is the first programmable optical processor. it combines the optics and silicon technology on the one standard board which can be use for the communication effectively. Lenslet's is the first designed optical digital signal processor. this processor is use for the intelligence, airport security, weather forecasting, for multimedia and for video compression purposes. It can also use for recognition purpose of voice and face. So this will open very great use in future as in military security purpose.

Optical transistor: Many optical transistors have been designed. We have a optical transistor based on the fabry-perot interferometer in which constructive and destructive interference show the ON the OFF the state of the interferometer [ref 5].

Optical logic gates based on silicon photonic crystal [ref 6]: silicon photonics based optical gates has been proposed by the scientists in which all logic gates are design in the 2D silicon photonics crystal structure using the light beam interference effects. this purposed idea not require so much of high power for the operation of these devices. This is very simple approach to integrated all-optical logic devices.

Design of optical switch for arithmetic operation[ref 7]: Ring resonator is designed as the optical switch which is use to calculate the all arithmetic operations. This is able to perform all two input sixteen logic operations.

Optical full-adder and full-subtractor based on electro-optic effect[ref 8]: Photonic based full adder and full-subtractor have been designed which gives optical adder and subtractor. This design has higher efficiency than the normal one

All Optical logic switches: Optical logic switch's example is Analog Gimbal-Mirror switch that directs light without the loss of info and require very less time to convey any information.

Optical fibers: optical fibers are use in communication for secure data transmission as it is smaller in size and more secure. No interference from radio frequencies is occurred inside the optical fiber so we can transfer the signal securely and without crosstalk.

Optical photodiode: Photodiode is the device which convert the photon light into the electrical signal.

1.4 Fundamentals of Plasmonics

When any light is incident on a metal, it generates collective oscillation of these electrons called Plasmons which have certain density. This plasmons can couple with the photons to create a quasiparticle known as Plasmon Polaritons. Researchers are now moving to plasmonics from the photonics as it give the new advantage in optical communication. This created electron density can carry huge amount of data in network. We have already stated that one day electromagnetic wave will be replaced the electronic circuits or electronic computing. Photonics crystals have the diffraction limit because of it closely packed light wave. So we have the plasmonic as a new technique which is use to design nanoscale dimension devices in optical communication.

Researchers state that if we propagate the light at the surface of the metal-dielectric surface it gives more confinement of the wave. This result in the Surface Plasmon Polarition (SPP). Surface Plasmon polarition are the electron oscillation which exists at the metal-dielectric interface or between metal-air interfaces. SPPs are propagate along the metal-dielectric or metal-air interface until it loss it's all energy in the metal or by scattering or by diffraction etc. SPP have lower amount of energy than the volume region. SPPs creates the motion in the metal creates EM (electromagnetic) waves outside the metal means in the air or in the dielectric.

1.5 Plasmonic waveguide

Waveguide are designed for the many applications and have very important role in the integrated circuits. To make the more integrated device we need very compact circuits, for this requirement we use the high refractive index waveguides. Waveguide which have the silica or air as a cladding with low index core. Light confinement is better in the silica based waveguide. In this waveguide light plays role with T.I.R. effect at the boundary due to high refractive index of the cladding with respect to core region.

Silicon waveguides are compatible with CMOS (Complementary metal–oxide–semiconductor) technology that's why this give us the chance for integrating electronics and the photonics at the same platform and having more interesting applications. Silicon waveguide have very low losses and have wide use in communication. Diffraction limit is there in the silicon based waveguide because of photons, for remove this another emerging technology is plasmonics in which wave travel inside the waveguide with the principle of surface plasmons polaritons (SPP) along the metal-insulator-metal (MIM) surface or metal-insulator (MI) surface.

Plasmonics waveguide are designed with the smaller dimension and have the shorter wavelength which can remove the diffraction limit. So this smaller dimension also increased the integration density. Many kind of plasmonic waveguides has been designed for various application. As metal have the complex refractive index, which gives the propagation losses inside the waveguide. We want a waveguide which have the less losses, high power density, and large confinement of the wave inside the waveguide. We have popular plasmonics based waveguides examples are dielectric loaded surface Plasmon waveguide(DLSPW)[ref 12], Plasmonic slot waveguide[ref 13],and hybrid Plasmonic waveguide (HPWG)[ref 14].

Chapter-2

TOOLS AND TECHNIQUES

All the numerical analysis has been performed in COMSOL Multiphysics®. Comsol Multiphysics® is a commercial software package which uses advanced numerical methods for solving and simulating the physics based problems and for mathematical modeling [ref 1]. COMSOL Multiphysics analysis is based on finite element method and comes with different modules to solve various physics and engineering problems. In this work RF module has been used to solve Maxwell's equations in frequency domain calculate electric and magnetic field distribution in the device and power obtained at the output port. Algorithm employed in the solving the Maxwell's equation is Finite Element Method (FEM), which is more accurate than another commonly used method called Finite Difference Time Domain (FDTD). FEM based COMSOL multiphysics® software provides a high range simulating methods for the controlling the complexity of the model.

Finite element method (FEM) was originally used in structural engineering. However due to its reliability, robustness and accuracy, it was later implemented in other fields of engineering including Electromagnetic (EM). There are others method as well, like finite difference method (FDM), method of moment (MOM), Method of Lines, etc, which are easier and simpler but less accurate than the FEM. FEM is more powerful method to solve the problems which involve the inhomogeneous media and having complex geometries. Furthermore, it can used complex values of relative permittivity and permeability without any convergence issues.

Finite element method involves basically the four step procedure to solve any problem in comsol multiphysics® software:

- Discretizing the full problem region into the finite number of smaller sub regions or element.
- Now derive the equation for the each of these sub region or element.
- Bring together all these equation into the solution region.
- Now solve these all equations obtained in previous step.

Discretization step involves dividing the region into the smaller sub domains, called finite element. That's why this process called as Finite element method.

A major limitation associated FEM is that the analysis of any problem is slow and very time consuming process. But COMSOL has a feature to bypass this limitation. It has a node and element generating scheme, which is called as mesh generator. Automatic mesh generation (AMG) not only reduces the time consumption in the problem solving but also reduces the human error which can occur when data preparation is performed. AMG basically reduce the input data that is required to solve any particular problem. And when we join this (AMG) automatic mesh generation program with computer graphics it become very advantageous because now the output can be monitored visually.

Advantages of FEM:

- Complex geometry can be easily solve by this method.
- This process involves the all dissimilar material properties.
- Very good and easier representation of any solution.
- It also included all the local effects.
- This method is less time consuming method, reliable and gives more accurate solution.
- It analyses the geometry with suitable boundary conditions,
- It method can be use to analyse any type of irregular shaped geometry.

Finite element method (FEM) is recently gained more popularity over the finite difference method (FDM) which is rather easier and simpler than FEM. But FEM deals with all the complex geometries while the FDM is restricted only to some basic figures like rectangular shape. So it can be stated that the FDM is a special case of FEM or in more precise words the first order FEM is identical to FDM poisons equation, FEM has also very higher approximation techniques than FDM that's why now a day's FEM is most likely used tool to solve the mathematical and physics problem.

Chapter-3

Literature review

1. Gordon E. Moore state that "With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65000 components on a single silicon chip. The future of the integrated electronics is the future of electronics itself. with the help of integrated electronics devices push the science into the new areas. Integrated (ckts) will provide automatic control for automobiles, and integrated ckts will also switch the telephone (ckts) and perform high data processing. the improved reliability made possible by integrated circuits will allow the construction of larger processing units. So there need to increase more number of components per integrated circuits [ref 4].

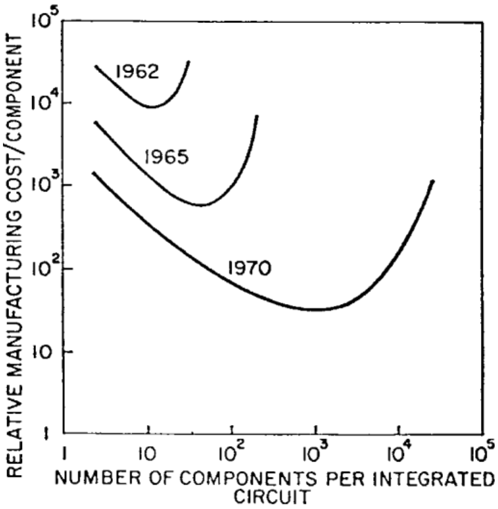

Figure 1 Increase The Number Of Component Per Integrated Circuit[ref 4]

2. Rashid Zia, Anu Chandran and Mark L. Brongersma[2005] gave the An approximate model is derived by a ray-optics interpretation that is consistent with previous investigations of the Fresnel relations for surface Polaritons reflection. Although surface Polaritons modes supported by finite-width interfaces can guide electromagnetic energy in three dimensions, we demonstrate for the first time to our knowledge that such modes can be modeled by the solutions of two-dimensional dielectric slab waveguides. This model is compared with modal solutions for metal stripe waveguides obtained by full vectorial magnetic-field finite difference methods.

The field-symmetric modes of such waveguides are shown to be in agreement with the normalized dispersion relationship for analogous TE modes of dielectric slab waveguides. Lateral confinement is investigated by comparison of power density profiles, and implicationsfor the diffraction limit of guided polariton modes are discussed.

3. Rashid Zia, Mark D. Selker, and Mark L. Brongersma[2005] have studied the leaky and bound modes of Surface Plasmon Waveguides. While theoretical studies of finite width plasmonic waveguides have focused on the bound modal solutionsof metallic structures in homogeneous or near-homogeneous dielectric matrices, experimental studies have mainly probed the leaky surface plasmon modes along the air-exposed surfaces of metallic stripes on glass substrates. Combining a full-vectorial, magnetic field finite-difference method with complex coordinate stretching perfectly matched layer boundary conditions, we have solved for both the leaky and bound modes of metallic slab and stripe waveguides. Solutions for the leaky modes excited via attenuated total reflection in the Kretschmann configuration provide added insight into the results of recent near and far-field experimental studies. For these cases, an analytical approximation for the number of allowed modes as a function of waveguide width is derived based upon the guidance condition of dielectric waveguide theory. Then, consistent with a ray optics interpretation for surface plasmon-polariton propagation, a direct comparison is made between our simulations and published results with regard to field profiles and propagation lengths [ref 5].

4. Pierre Berini, has studied the Plasmon–polariton modes guided by a metal film of finite width. The properties of purely bound plasmon–polariton modes guided by a symmetric thin metal film of finite width are described for what is believed to be the first time, and a suitable mode nomenclature for identifying them is proposed. The dispersion characteristics of the modes as a function of film thickness are presented. It has been found that long-range plasmon–polariton modes exist in a symmetric film structure and that one of them may be suitable for optical signal transmission [ref 22].

5. P. Phongsanam et al., proposed the half adder/ subtracter optical circuit in which he use bright soliton for the 1 and dark soliton for 0 symbol using this dark bright soliton

he performed addition and subtraction. In this model, addition and subtraction performed simultaneously via the add drop optical filter. Optical filter is basically used for addition and subtraction arithmetic operation. This is the advance type of optical circuits [ref 16].

6. Yulan Fu et al., proposed 2-D silicon photonic crystal all optical logic gates, OR, XOR, XNOR, NOT and NAND gat in which we use the photonic geometry with the light interference effect and concluded that ON and OFF stage is obtained by the interference phenomenon. 20dB intensity contrast ratio exists between the output states [ref 6].

7. Ajay Kumar et al., has proposed full adder and full subtractor circuits based on the principle of Mach-Zehnder interferometers (MZI) and get the better results of the parameters such as extinction ratio, power imbalance, crosstalk and transition loss [ref 8]. He use the beam propagation method to analysis all these parameters. Purposed design is this. The optical switching phenomena has been studied and its efficient application to construct the fulladder/subtractor (A/S) has been projected. The paper constitutes the mathematical description of proposed device and thereafter compilation using MATLAB. The analysis of various factors such as crosstalk, extinction ratio, power imbalance and transition loss has been presented. The desirable device parameter has been examined in order to obtain the optimum best influencing parameter. The work is carried out by simulating the proposed device with Beam propagation method and using the observed results to study the characteristics of influencing parameters in consideration with the device parameters.

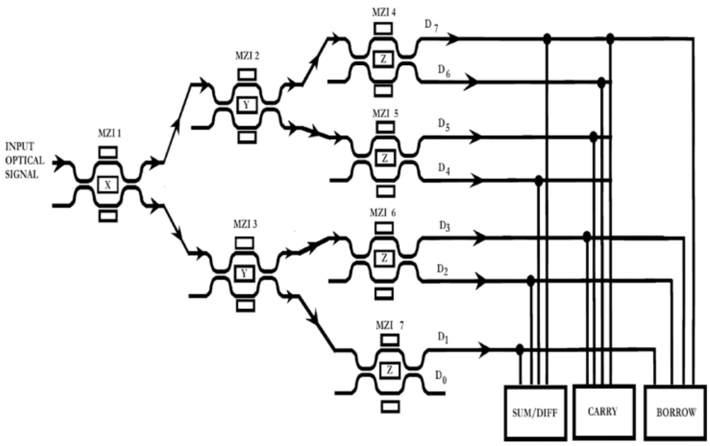

Figure 2 Diagram Of Full Adder/Subtractor Using MZIs [ref 8]

8. J.K. Rakshit et al., purposed the all optical switch which are based on the principle of ring resonator and performed the arithmetic operation. The ring resonator is create change in the refractive index which results shift in the wavelength and produce the results of arithmetic operations. In his design he uses the cascading of the ring resonator and studied it overall transfer function. He uses cascading of three MRRs (micro ring resonator) which is capable to produce all two input sixteen logic operations [ref 7].

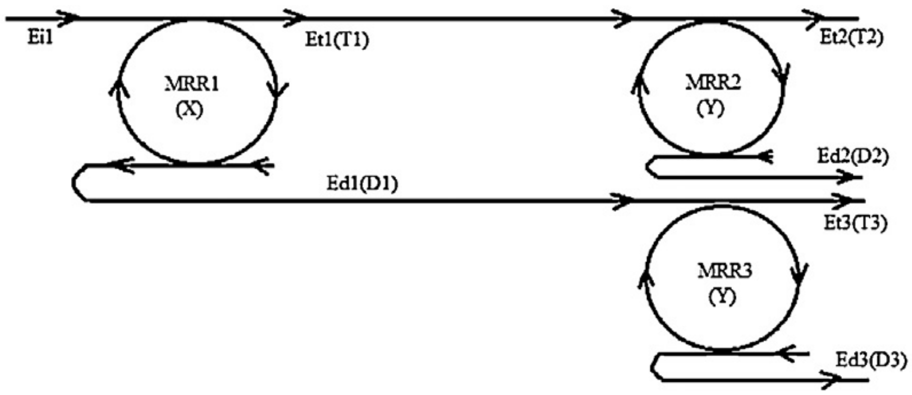

Figure 3 cascaded micro-ring resonator[ref 7]

9. Qianfan Xu and Michal Lipson purposed the the optical logic AND and NAND based on silicon micro-ring resonator.he use two control signals have bit rate of 310 Mbit/sand pulse width of 200 ps in the (MRR) in which it will change the refractive index of the matrial and produce the output of the logic gates [ref 10].

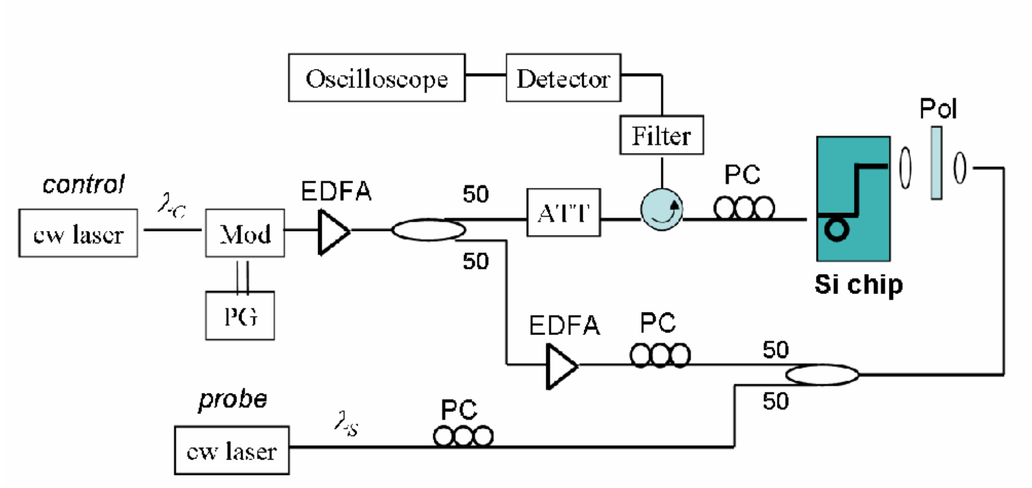

Figure 4 All Optical Logic Using Silicon Ring Resonator [ref 10]

10. Rashid Zia, Mark D. Selker, Peter B. Catrysse, and Mark L. Brongersma, has gave the design of the plasmonic waveguide in which the propagating wavelength shorter than those are in vacuum [ref 21]. He studied that by changing the geometries and the material of the waveguide we can travel diferent sub wavelength. This modal fulfill the promise that Plasmonic waveguide truly fulfill the subwavelength waveguides. To improve the trade off we can select the wavelength and proper material used for waveguide.he state that the gooves and holes in a metallic layer would be the ideal system for sub wavelength waveguides in 2D structure.

11. Dilip Kumar Gayen et al., purposed optical adder/subtractor based on terahertz optical asymmetric demultiplexer(TOAD),can be use to perform the fast central processor unit using optical hardware components.this is use to design this is use an integrated circuits to perform binary addition and subtraction.

12. Najmeh Nozhat and Nosrat Granpayeh purposed the T shaped switch based on the square shaped plasmonic ring resonator by the method of (FDM) [ref 11].Is purposed model include AND and NOR logic each with two cascaded T-shaped switches. This ring resonator is basically work due to the nonlinear Kerr effect.when light is comes in the resonator it changes the refractive index of the medium and coupled with the

light and produce the result 1 and 0. These result is also obtained in my work at a initial level.

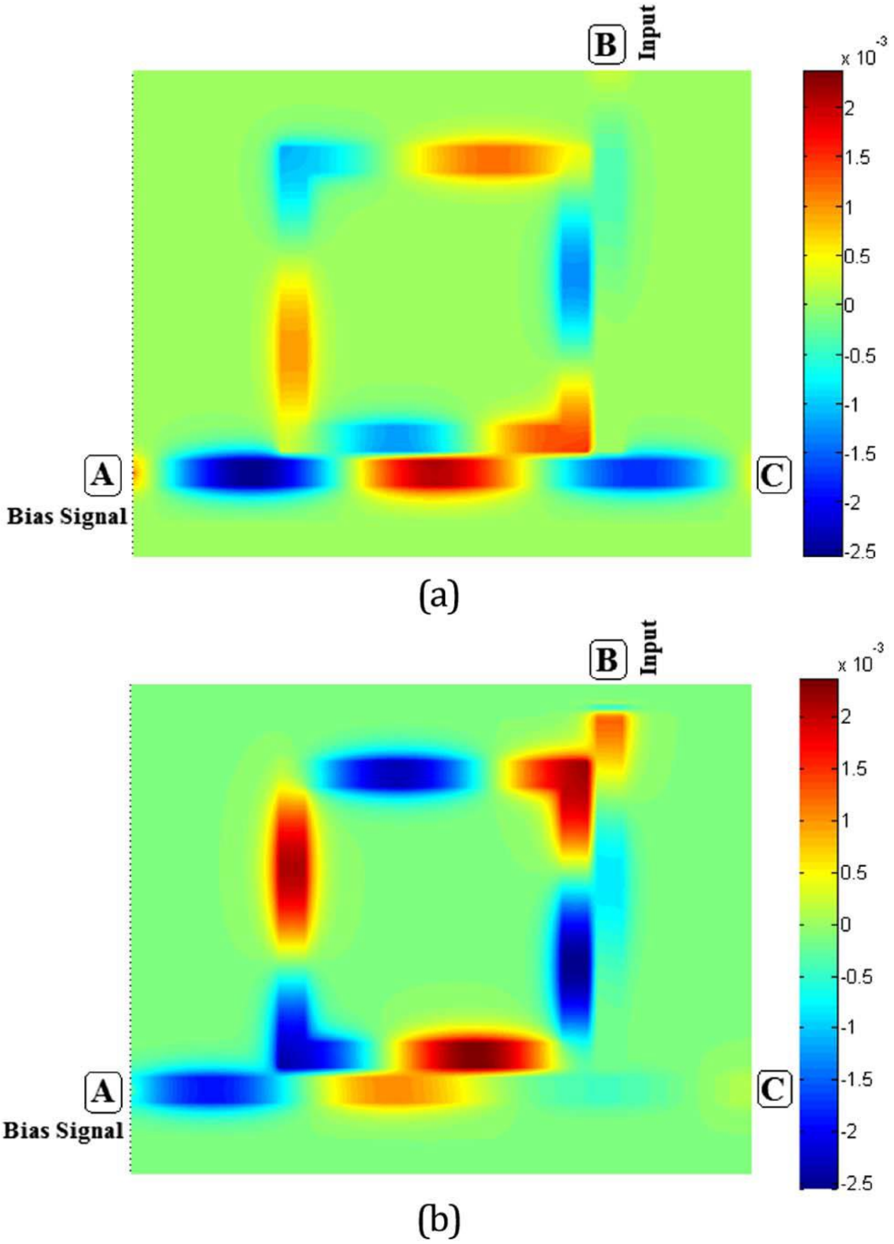

Figure 5 Result Obtained In Comsol Using Ref [11]

13. H. John Caulfield and Jonathan implemented boolean logic that is based up on fuzzy logic. He analysis the vector logic and optical vector logic. This model work in every application of the OVL.he designed simple OVL gate is the VXOR gate that fulfill

many use,also use for encryption and decryption of the data. He signed the Gates on the basis of the Fuzzy Principle [ref 23].

14. Parisa Andalib and Nosrat Granpayeh[2008] proposed an ultra compact all optical crystal AND gate based on nonlinear ring resonator, consisting of two Kerr nonlinear photonic crystal ring resonator inserted between three parallel lie defects. They have employed a Si nanocrystal as the non linear material for its appropriate nonlinear properties. They have simulated and analyzed by Finite difference time [FDT] domain and plane wave expansion methods. Due to instantaneous response of Kerr effect nonlinearity, the lower limit of modulation frequency is dictated by inherent cavity response time, is about 120 Gbits/s [ref 24].

15. Pierre Berini studied Plasmon-polariton modes guided by a metal film of finite width bounded by different dielectrics. The properties of some purely bound plasmon-polariton modes guided by an asymmetric waveguide structure composed of a thin lossy metal film of finite width supported by a dielectric substrate and covered by a different dielectric superstrate are presented for what is believed to be the first time. The mode spectrum supported by these structures is quite different from the spectrum supported by corresponding asymmetric slab structures or similar finite-width symmetric waveguides. Unlike these limiting cases, the dispersion with film thickness exhibits an unusual oscillatory character that is explained by a “switching” of constituent interface modes. This mode switching is unique to asymmetric finite-width structures. Above a certain cut-off film thickness, the structure can support a long-ranging mode and its attenuation decreases very rapidly with decreasing film thickness, more so than the long-ranging mode in symmetric structures. Also, the cutoff thickness of the long-ranging mode is larger than the cutoff thickness of the long-ranging mode in the corresponding asymmetric slab waveguide, which implies that propagation along finite-width films is more sensitive to the asymmetry in the structure than propagation along a similar slab structure. Both of these results are potentially useful for the transmission and control of optical radiation [ref 25].

Chapter 4

DESIGN AND ANALYSIS

4.1 Theory

Plasmonics as the new technology: When any light is incident on a metal, it generates collective oscillation of these electrons called Plasmons which have certain density. This plasmons can couple with the photons to create a quasiparticle known as Plasmon Polaritons. A surface plasmon polariton is highly confined to the metal-dielectric interface (SPP). SPPs propagate along the metal-dielectric or metal-air interface until it loses all in the volume region. Electron wave travels on the metal side of the interface while the EM (electromagnetic) waves outside the metal on the dielectric or air side.

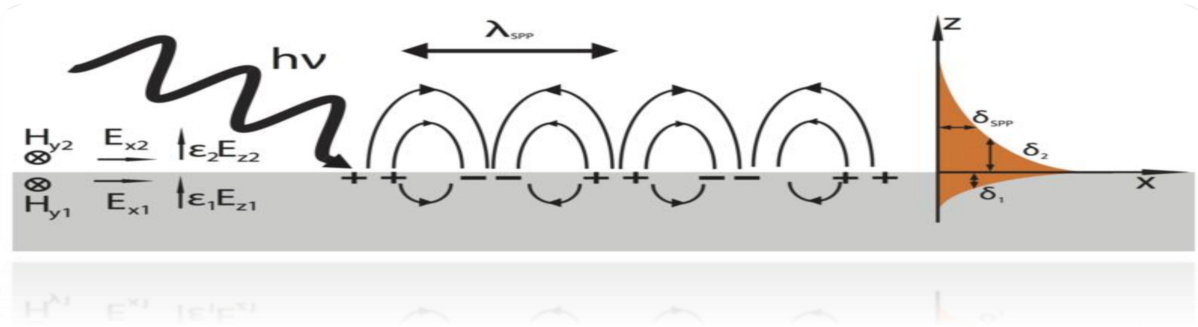

Figure 6 Formation Of SPP At The Metal And Dielectric Interface[ref 17]

Surface plasmons have the same frequency as the incident exciting wave but a smaller wavelength. This feature can be exploited to make plasmons travel in nanowires working as data lines in an optical microprocessor. Plasmonics based devices have more effciency and faster response that electronic ones. They are used in medicine for cancer detection and treatment. Plasmonics open the way to the nanoscale integration and also give the new field such as Meta materials.

When EM waves are coupled to the Surface Plasmons at the interface of the metal-dielectric surface then this electromagnetic waves propagate along the interface and act like a guided wave. Such a structure is called a Plasmonics waveguide or SPP waveguide.

4.2 The Maxwell's Equations

As it is known that surface Plasmon polaritons are the EM waves. To study how SPP travel, Maxwell's Equation should be applied on the SPP produced at the surface between the metal and dielectric interface. There are four basic equation which need to solved. By using these basic equations we will come to know about the spatial field profile and dispersion of the propagating waves.

$$\nabla \cdot D = \rho_{ext} \tag{4.1a}$$

$$\nabla \cdot B = 0 \tag{4.1b}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{4.1c}$$

$$\nabla \times H = J_{ext} + \frac{\partial D}{\partial t} \tag{4.1d}$$

These equations have D as the dielectric displacement, E as the electric field, H as the magnetic field, B as the magnetic flux density, charge density(ρ_{ext}), and J_{ext} as the current density.

When we apply above boundary conditions in between the conductor and the dielectric we can analyse the all the physical field and dispersion properties of SPP.

In absence of any external charge and current density, curl of the equation will be given by:

$$\nabla \times \nabla \times \nabla = -\mu_o \frac{\partial^2 D}{\partial t^2} \tag{4.2}$$

For without any variations, if $\varepsilon = \varepsilon(r)$ over distances on the order of one wavelength, we have simplifies equation is

$$\nabla^2 E - \frac{\varepsilon}{c^2}\frac{\partial^2 E}{\partial t^2} = 0 \tag{4.3}$$

After assuming electric field is harmonic time dependent as $E(r,t) = E(r)\ e^{-i\omega t}$, the wave equation is

$$\nabla^2 E - k_o{}^2 \varepsilon E = 0 \tag{4.4}$$

We have defined as $k_o{}^2 = \frac{\omega}{c}$, this equation 4.4 called as Helmholtz equation. Next, we have define the propagation geometry for simplicity we assume one dimension problem as shown in fig 7. Wave travel along the x-direction and there is no variation in field in the y direction i.e. $\varepsilon = \varepsilon(z)$. Propagating wave can be described as $E(x, y, z) = E(z)e^{\beta ix}$. This β is the complex parameter called propagation constant. After substituting it in the above 4.4 equation we have

$$\frac{\partial^2 E(z)}{\partial z^2} + (k_o{}^2 - \beta^2)\, E = 0 \qquad (4.5)$$

A similar expression we can derive for the Magnetic field .this equation 4.4 is the starting point for the general analysis of guided EM modes in the waveguides.

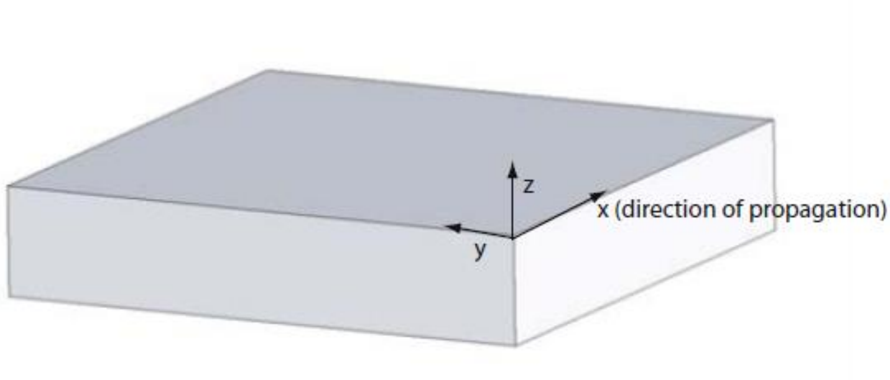

Figure 7 Image Showing Wave Propagation Along x Direction In Cartesian Coordinates[ref 18].

For finding the spatial field profile and dispersion of the propagating waves, we will split the expression for the different field components of E and H. for TM modes, where magnetic field has non zero components on the plane parallel to the wave propagation only E_x , E_z and H_y exists and the wave equation for TM wave is :

$$\frac{\partial^2 H_y}{\partial z^2} + (k_o{}^2 \varepsilon - \beta^2)\, H_y = 0 \qquad (4.6)$$

With electric field components

$$E_x = -\frac{1}{\omega \varepsilon_o \varepsilon} \frac{\partial H_y}{\partial z} \qquad (4.7)$$

$$E_z = -\frac{\beta}{\omega \varepsilon_o \varepsilon} H_y \qquad (4.8)$$

for TE modes the same set of equations with only H_x , H_z and E_y are non zero components with as

$$H_x = i\frac{1}{\omega\mu}\frac{\partial E_y}{\partial z} \tag{4.9}$$

$$H_z = \frac{\beta}{\omega\mu_o} E_y \tag{4.10}$$

TE wave equation is:

$$\frac{\partial^2 E_y}{\partial z^2} + (k_o{}^2\varepsilon - \beta^2)\, E_y = 0 \tag{4.11}$$

4.3 Surface Plasmon Polaritons at a single interface:

The simplest geometry that can sustain the SPP is the flat single interface between the dielectric (z>0) which have the positive real dielectric constant ε_2 and a metal (z<0) having the dielectric function ε_1 as shown in fig 8. As we know metal have negative real part of dielectric constant $Re[\varepsilon_1]<0$, below the bulk Plasmon frequency ω_p , it causes an exponentially decaying evanescent field in the perpendicular direction of propagation.

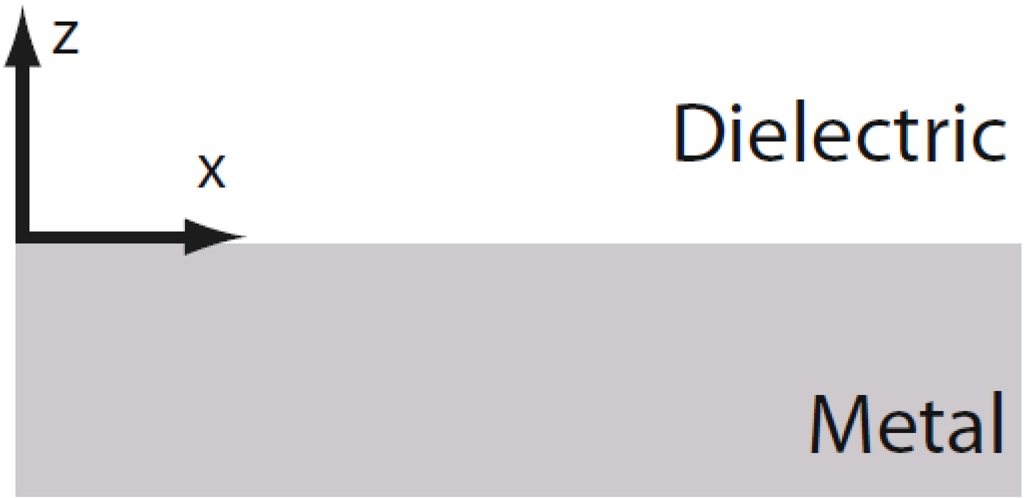

Figure 8 Image Surface Plasmon Polaritons Between The Metal And The Dielectric(Image Taken From Ref [18]).

TM equation for the first half z>0

$$H_y(z)= A_2 e^{i\beta x} e^{-k_2 z} \tag{4.12a}$$

$$E_x(z)= \frac{iA_2 k_2 e^{i\beta x} e^{-zk_2}}{\omega\varepsilon_0\varepsilon_2} \tag{4.12b}$$

$$E_z(z)=\frac{-\beta A_1 e^{i\beta x} e^{-k_2 z}}{\omega\varepsilon_0\varepsilon_2} \tag{4.12c}$$

Here A_2 is the constant

$$({k_2}^2 = \beta^2 - {k_0}^2\varepsilon_2) \tag{4.12d}$$

For the region of metal z<0

$$H_y(z)= A_1 e^{i\beta x} e^{k_1 z} \tag{4.13a}$$

$$E_x(z) = \frac{-i\, A_1 k_1 e^{i\beta x} e^{k_1 z}}{\omega\varepsilon_0\varepsilon_1} \tag{4.13b}$$

$$E_z(z)= \frac{-A_1 \beta e^{i\beta x} e^{k_1 z}}{\omega\varepsilon_0\varepsilon_1} \tag{4.13c}$$

Here A1 and A2 are the constants

$$({k_1}^2 = \beta^2 - {k_0}^2\varepsilon_1) \tag{4.13d}$$

When the operating frequency is less than the ω_p and the dielectric ε_2 is negative and relation between β and k_0 is $\beta^2 - {k_0}^2\varepsilon_2 > 0$. Now we are applying the boundary condition at the metal-dielectric interface and as per the continuity of electric field and the Displacement,

$$D_{p1}= D_{p2} \tag{4.14a}$$

$$E_{t1} = E_{t2} \tag{4.14b}$$

At the interface z = 0 between the metal and the dielectric. From the 4.14a boundary condition, $D_z = \varepsilon_1 E_z = \varepsilon_2 E_z$ we have the

$$A_1 = A_2$$

From the 4.14b boundary condition we get

$$\frac{A_1K_1}{\epsilon_1} + \frac{A_2K_2}{\epsilon_2} = 0 \qquad (4.15)$$

From which we have

$$\frac{k_2}{k_1} = - \frac{\varepsilon_2}{\varepsilon_1} \qquad (4.16)$$

Using as above all the equations we have arrive at a result

$$\beta = k_0\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}} \qquad (4.17)$$

this equation 4.17 is valid for conductor without or with attenuation. With the help of this expression we have derived dispersion graph in MATLAB®. Effective permittivity of observed by SPP is considered as ($\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}$), also we know similarly this equation exist for TE mode.

Or (z>0)

$$E_y(z)= A_2e^{i\beta x}e^{-k_2 z} \qquad (4.18a)$$

$$H_x(z)= - \frac{iA_2k_2e^{i\beta x}e^{-zk_2}}{\omega\varepsilon_0\varepsilon_2} \qquad (4.18b)$$

$$H_z(z)=\frac{-\beta A_2e^{i\beta x}e^{-k_2 z}}{\omega\varepsilon_0\varepsilon_2} \qquad (4.18c)$$

And for the (z<0)

$$E_y(z) = A_1e^{i\beta x}e^{k_1 z} \qquad (4.19a)$$

$$H_x(z) = \frac{-i\, A_1 k_1 e^{i\beta x} e^{k_1 z}}{\omega\varepsilon_0\varepsilon_1} \tag{4.19b}$$

$$H_z(z) = \frac{-A_1 \beta e^{i\beta x} e^{k_1 z}}{\omega\varepsilon_0\varepsilon_1} \tag{4.19c}$$

After applying boundary conditions again at the interface we have :

$$A_1 \,(\, K_1 + K_2 \,) = 0 \tag{4.20}$$

We know that condition of propagation is Re [K_1] >0, & the Re[K_2] >0, hence for the confinement of wave between the metal and the dielectric A = 0 and A=B=0. It indicates that TE modes cannot exists and only TM polarization exist for SPP.

Let us consider the upper half to be air(ε_1 = 1), and lower half to be metal with the negligible damping. Then by ideal drude model, $\varepsilon_2 = 1 - \frac{\omega_p{}^2}{\omega^2}$ .we can write the dispersion equation as the

$$\frac{\beta^2 c^2}{\omega_p{}^2} = \frac{\frac{\omega^2}{\omega_p{}^2}\left(\frac{\omega^2}{\omega_p{}^2} - 1\right)}{2\,\frac{\omega^2}{\omega_p{}^2} - 1} \tag{4.21}$$

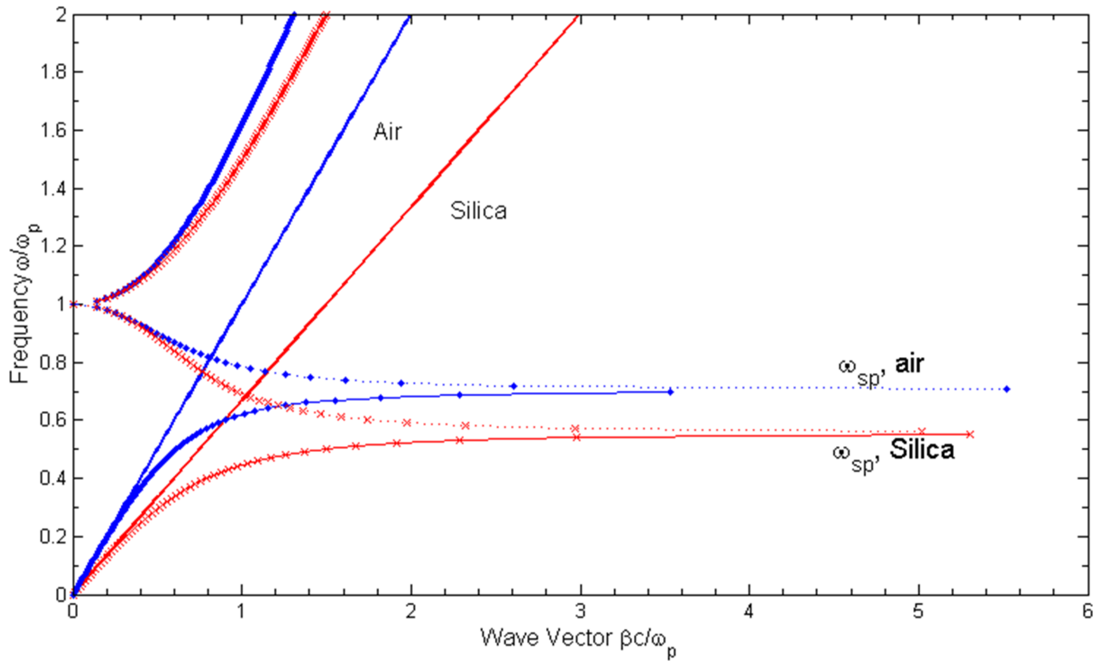

Figure 9 Dispersion Relation Curve Of SPP Between A Metal (Drude) With Negligible Damping Freq And Silica Interface.(Image Taken From Ref [18]).

In this graph the ω and the β both are normalized and we have taken the ε_2 = 1 in case air and ε_2 = 2.25 in case of silica. The continous and broken parts represent the real and imaginary part of β respectively. If the $\omega < \omega_p$ we have the $\varepsilon_2 < 0$ which satisfies our $\beta^2 - k_0{}^2\varepsilon_2 > 0$. When $\frac{\omega}{\omega_p}$ is between 0 and 0.71 ,we the real value of β, and propagation takes place in between metal and air. For propagation takes place for $\frac{\omega}{\omega_p}$ between 0 and 0.54. For propogating modes the upper limit of frequency is defined as:

$$\omega_{sp} = \frac{\omega_p}{\sqrt{1+\varepsilon_1}} \qquad (4.22)$$

from this equation for $\omega_{sp,1}$= $0.707\omega_p$ for air – metal and $\omega_{sp,2}$= 0.550 for air-silica.

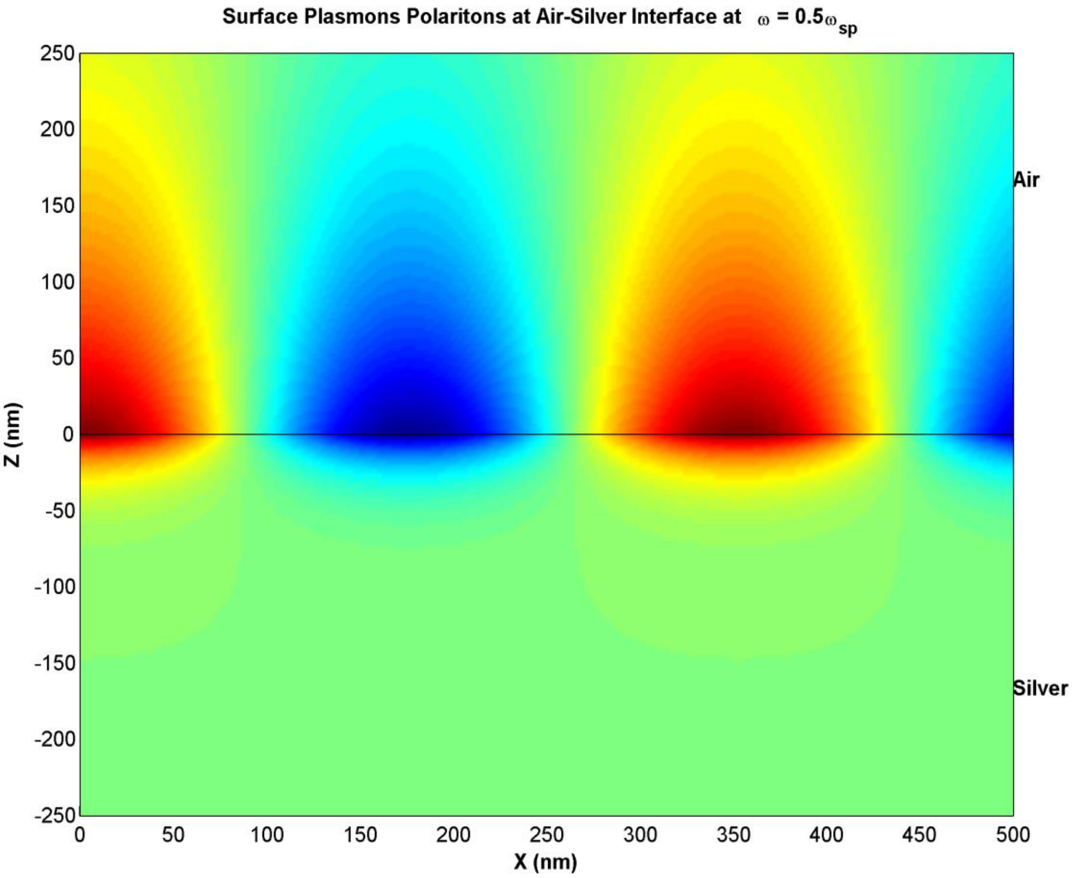

Figure 10 Image Obtained In Comsol Software at ω = 0.5ω_{sp}

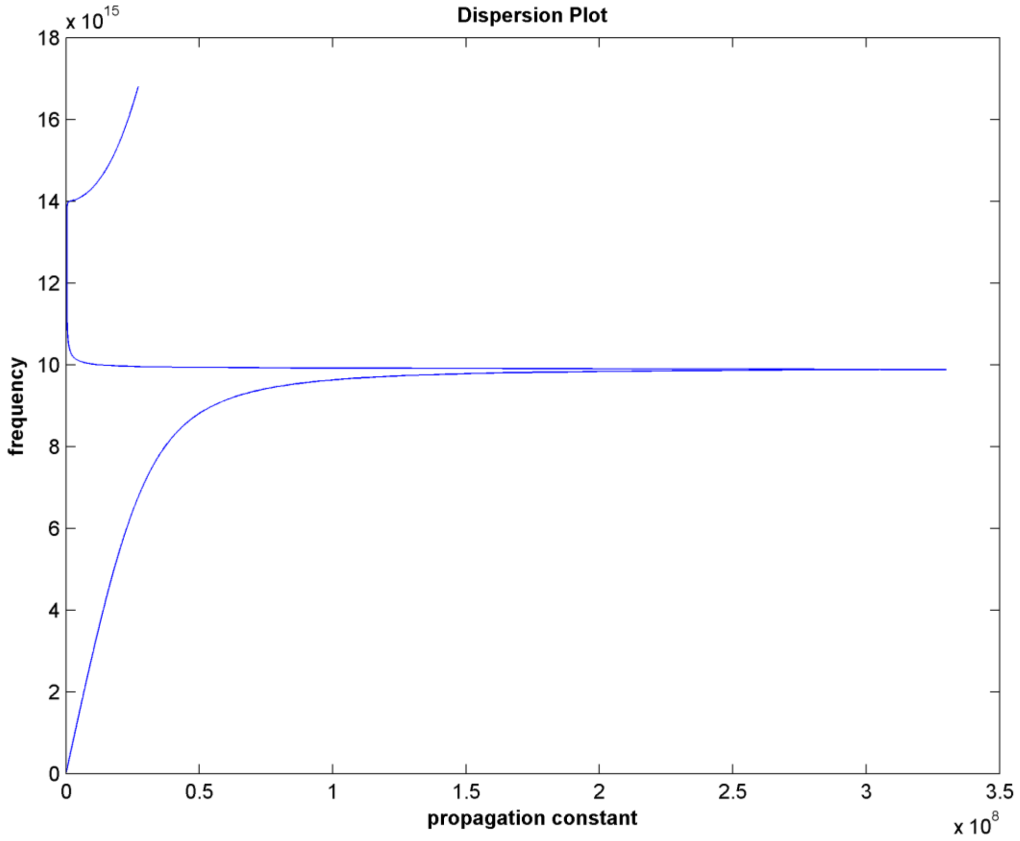

Figure 11 Obtained Dispersion Curve In MATLAB Software

In reality, metals are lossy and the field intensity of SPP decay by the factor of e^{-1} after travel some specific distance. That distance is called as the propagation distance and is defined as

$$L = \frac{1}{2\mathrm{Im}[\beta]} \tag{4.23}$$

4.4 Multilayer System

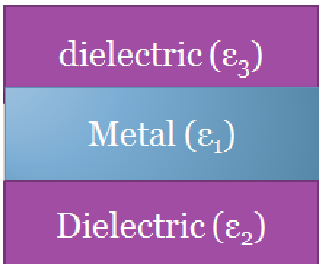

Figure12. Multilayer Structure IMI Type

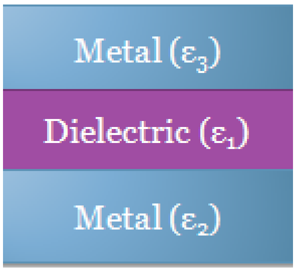

Figure 13 Multilayer Structure MIM Type

When metal and dielectric layers are alternatively arranged in the configurations shown in fig 12 and 13, it is called as multilayer system. In the insulator-metal-insulator (IMI) structure shown in fig 12, dielectrics extend till infinity on both sides and is taken and a thin film of metal with thickness 2a is encapsulated between them. Consider EM wave propagation along the x axis and the form of $e^{i(\omega t-\beta x)}$. The value of β for symmetric and anti symmetric mode is different for the different thickness of the metal layer. Convientialy we take the E_z as the symmetric SPP mode and have odd symmetry of E_x. Fields attenuate exponentially in the direction normal to the interface. This case in which symmetric branch in metal layer has the long L propagation length in lossy metal is referred as the long range SPP and the anti symmetric is referred as the short range SPP. If we keep the thickness of sandwiched material very narrow then the SPP generate at the both the interface will be overlap with each other to a large extent. These structures have the same equations for TM mode

z >a

$$H_y(z)= Ae^{i\beta x}e^{-k_3 z} \quad (4.24a)$$

$$E_x(z) = \frac{i\, Ak_3 e^{i\beta x}e^{-k_3 z}}{\omega\varepsilon_0\varepsilon_3} \quad (4.24b)$$

$$E_z(z)= \frac{-A\beta e^{i\beta x}e^{-k_3 z}}{\omega\varepsilon_0\varepsilon_3} \quad (4.24c)$$

For the z < - a

$$H_y(z)= Be^{i\beta x}e^{k_2 z} \quad (4.25a)$$

$$E_x(z) = \frac{-i\, Bk_2 e^{i\beta x}e^{k_2 z}}{\omega\varepsilon_0\varepsilon_2} \quad (4.25b)$$

$$E_z(z)=\frac{-B\beta e^{i\beta x}e^{k_2 z}}{\omega\varepsilon_0\varepsilon_2} \quad (4.25c)$$

The field is decayed exponentially in the cladding region (2 and 3) region. In the region between a the bottom and the upper interface, the field equation are

$$H_y(z)= Ce^{i\beta x}e^{k_1 z} + De^{i\beta x}e^{-k_1 z} \quad (4.26a)$$

$$E_x(z) = \frac{-i\,Ck_1 e^{i\beta x}e^{k_1 z}}{\omega\varepsilon_0\varepsilon_1}+\frac{i\,Dk_1 e^{i\beta x}e^{-k_1 z}}{\omega\varepsilon_0\varepsilon_1} \quad (4.26b)$$

$$E_z(z) = \frac{C\beta e^{i\beta x}e^{k_1 z}}{\omega\varepsilon_0\varepsilon_1}+\frac{D\beta e^{i\beta x}e^{-k_1 z}}{\omega\varepsilon_0\varepsilon_1} \quad (4.26c)$$

Now on applying the boundary conditions on both the interfaces we have these results

$$Ae^{-k_3 a}= Ce^{k_1 a} + De^{-k_1 a} \quad (4.27a)$$

At z=a and

$$Be^{-k_2 a}= Ce^{-k_1 a} + De^{k_1 a} \quad (4.28a)$$

$$-\frac{B}{\varepsilon_2}k_2 e^{-k_2 a}= -\frac{C}{\varepsilon_1}k_1 e^{-k_1 a} + \frac{D}{\varepsilon_1}k_1 e^{k_1 a} \quad (4.28b)$$

At z=-a we have the four equation for overlapped fields, H_y will satisfy the wave equation

$$k_i = \beta^2 - k_o^{\,2} \in_i \quad \text{(for i= 1,2,3.)} \quad (4.29)$$

In this multilayer system we have the dispersion relation between Propagation vector and the frequency.

$$e^{-4k_1 a} = \frac{\frac{k_1}{\varepsilon_1}+\frac{k_2}{\varepsilon_2}}{\frac{k_1}{\varepsilon_1}-\frac{k_2}{\varepsilon_2}} \frac{\frac{k_1}{\varepsilon_1}+\frac{k_3}{\varepsilon_3}}{\frac{k_1}{\varepsilon_1}-\frac{k_3}{\varepsilon_3}} \quad (4.30)$$

In special case in which $\in_2 = \in_3$ and then $k_2 = k_3$ the equations become

$$\tanh k_1 a = -\frac{k_2 \in_1}{k_1 \in_2} \quad (4.31a)$$

$$\tanh k_1 a = -\frac{k_1 \in_2}{k_2 \in_1} \quad (4.31b)$$

in which we have $k_2 = \beta^2 - {k_0}^2 \varepsilon_2$ and $k_1 = \beta^2 - {k_0}^2 \varepsilon_1$

4.5 Waveguide based optical logic gates

General Design parameters

We have adopted the metal-insulator- metal type waveguide to design the logic gates. In which silver is taken as metal and insulator has permittivity of 4.

Wavelength (λ) = 650 nm

Frequency (f) = $\frac{c}{\lambda}$

Permittivity of silver metal at 650 nm ($\in_m$) = -15-0.04i

Refractive index of the silver metal at 650 nm (n_m) = 0.051585-3.9046i

Permittivity of the dielectric ($\in_d$) = 4

4.5(a) NOT GATE

We have design NOT gate with MIM structure as shown in fig 14. It has three ports: one port for biasing signal, second port for input light wave and third port for the output. The length of each waveguide is equal λ and thickness is 100 nm. The gate has been made up of fusion of horizontal waveguide to another waveguide which is inclined with angle θ = 145 degree as shown in fig 14.

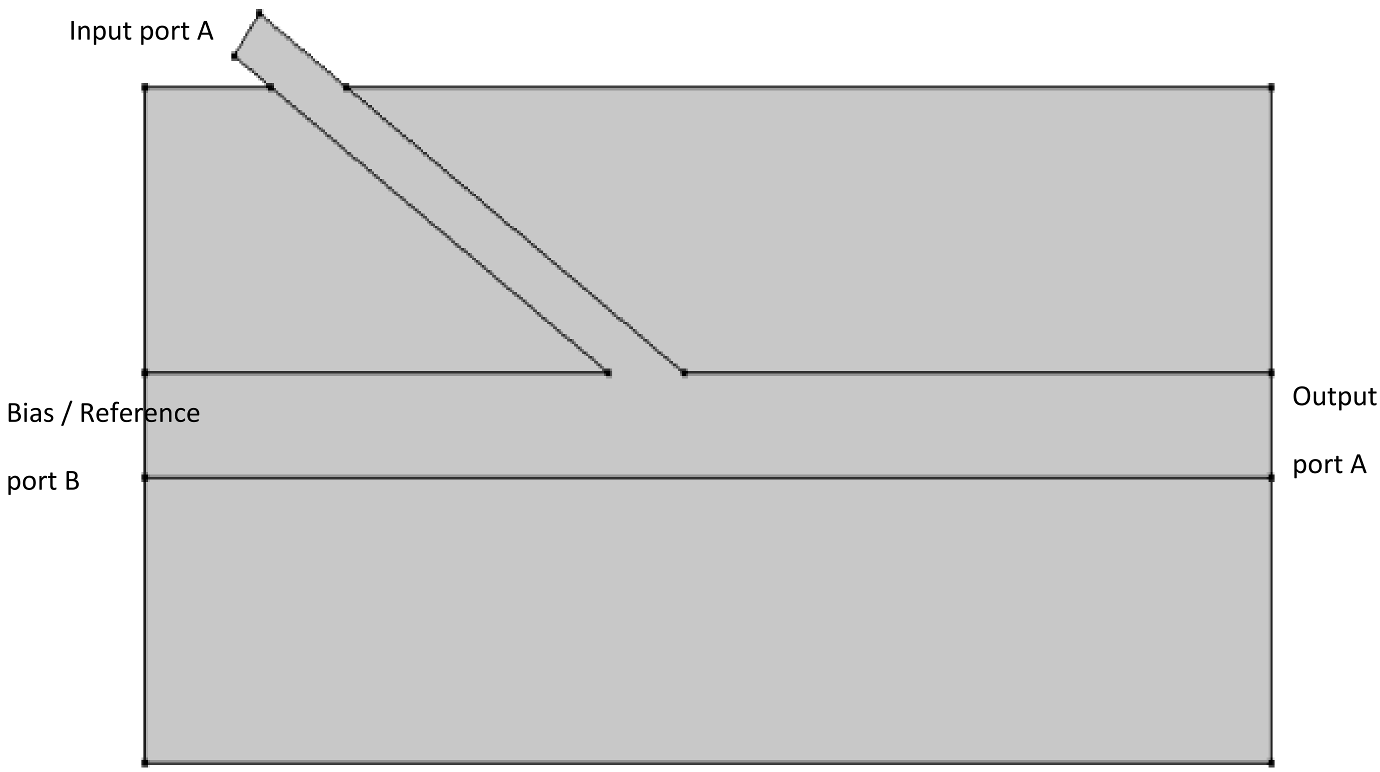

Figure 14 Design Of NOT GATE

A bias signal at the wavelength of 650nm is always launched into reference port. When we launch a signal which is out of the phase w.r.t bias signal into the input port, due destructive interference we get only 6% of input power at the output port as shown in fig.(15). This shows the OFF state condition of NOT gate. In the absence of the input signal the power from bias port reaches the output port uninterrupted, after facing small ohmic loss.

The resultant magnetic field of NOT gate OFF stage is obtained as shown in fig 15

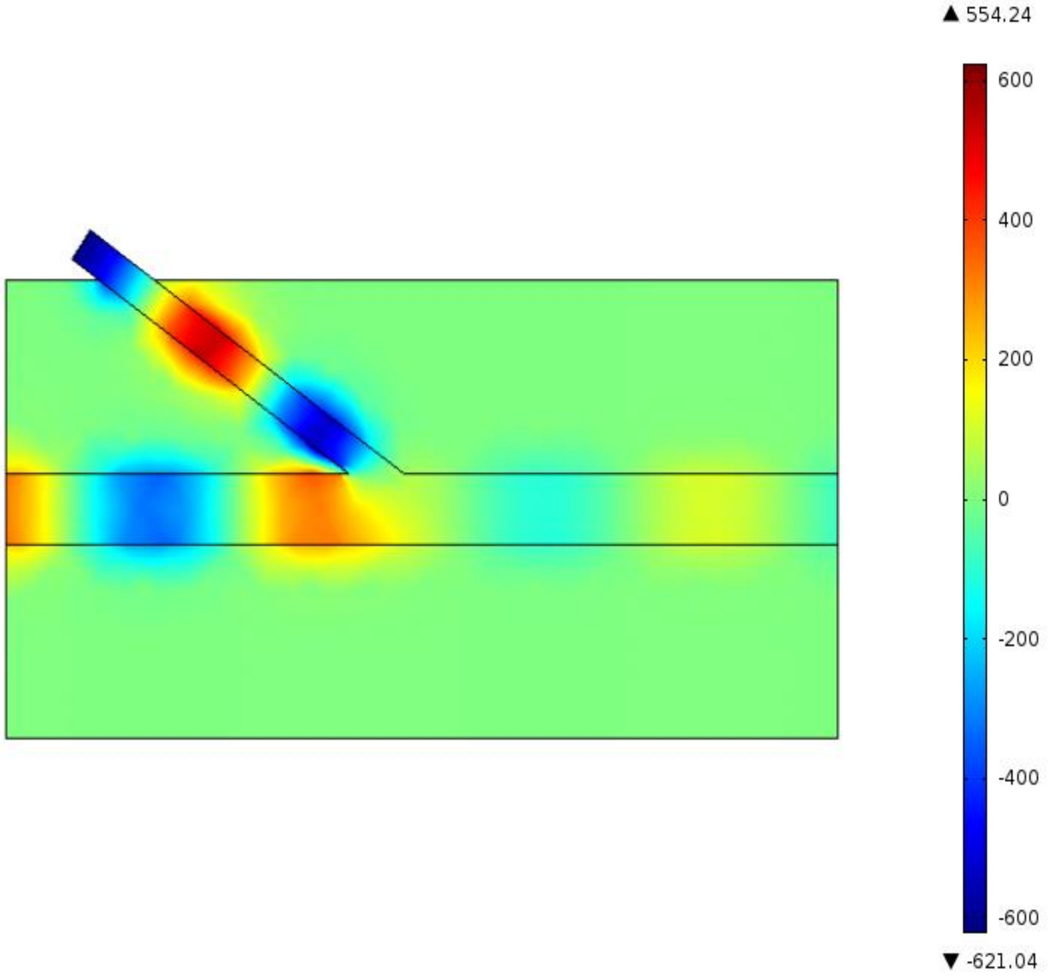

Figure 15 Magnetic Field Distribution Obtained At Output OFF State

In the absence of input signal 62% on bias power reaches the output port . This shows the ON state condition of NOT gate. The magnetic field distribution obtained for the NOT gate for ON stage is shown in fig 16.

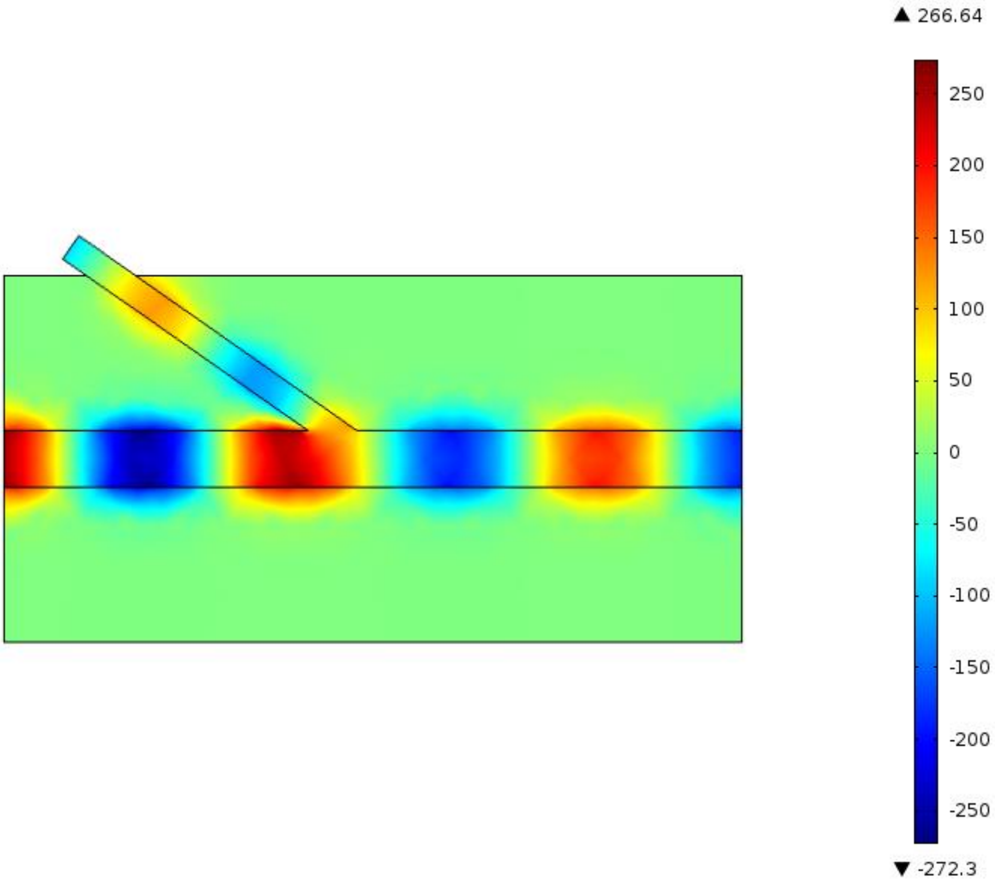

Figure 16 Magnetic Field Distribution Obtained At Output ON State

It should be noted that the definition of threshold condition is as follows:

When output power is greater than 40% of input power it is considered as ON stage and if output is less than 20% it is considered as OFF stage**.** All the gate have been designed in accordance with this definition.

Truth Table for NOT gate:

A (input port)	B (reference port)	C (output port)	P_C/P_B
0	1	1	0.61569
1	1	0	0.07324

4.5 (b) OR GATE

We have design an OR gate using three MIM waveguides. It has thre ports out of which two ports are input ports and third port is the output port. In the design, we have the fusion of one horizontal waveguide with the two straight waveguide with the angle θ = 170 and θ=-170 degree as shown in figure 17.

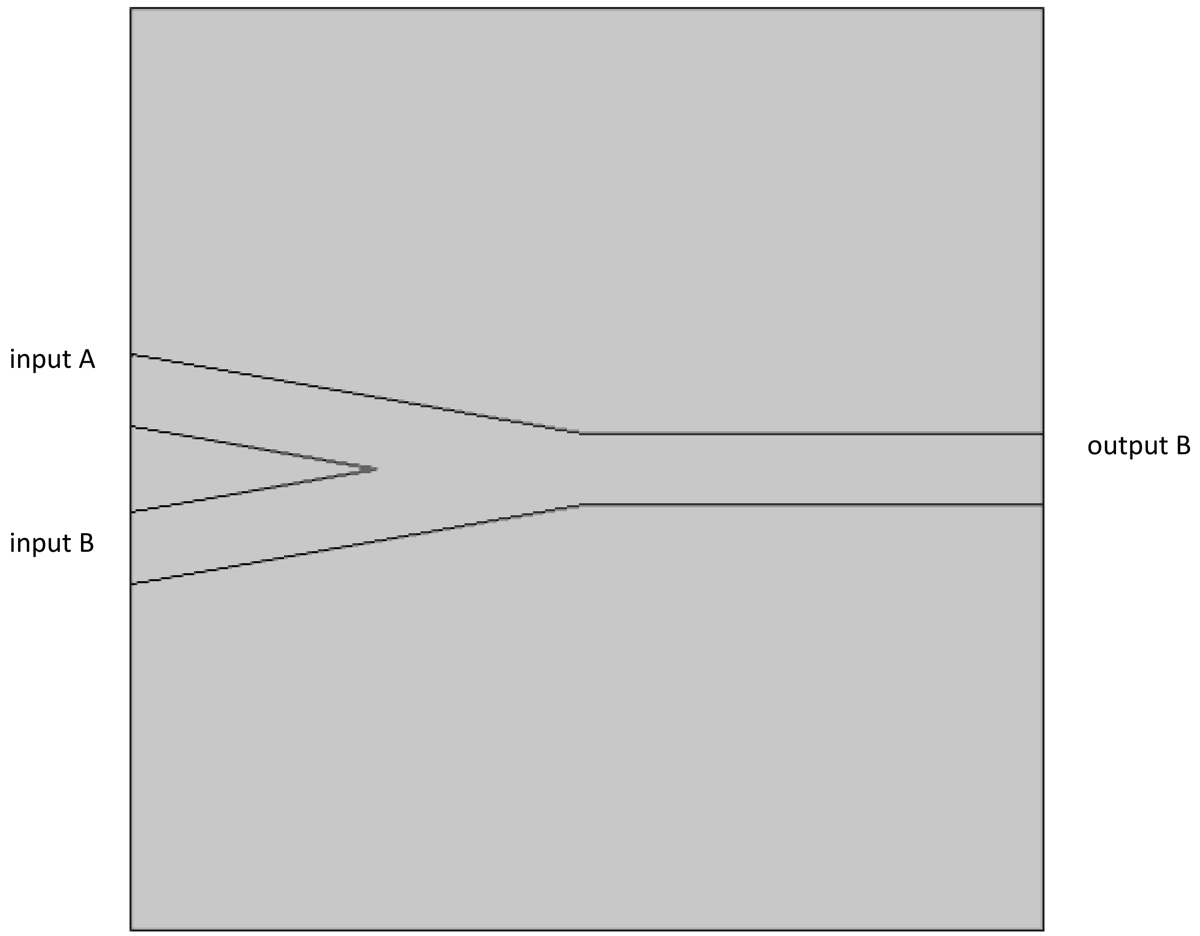

Figure 17 Design of OR gate

The input signals have the wavelength of 650nm. Whenever there is no input signal at all, output power is zero and it is considred OFF state of the OR gate. In any other case, output has some sgnificant amount of power and its state is ON.

Magnetic field is obtained in this case is shown in fig 18.

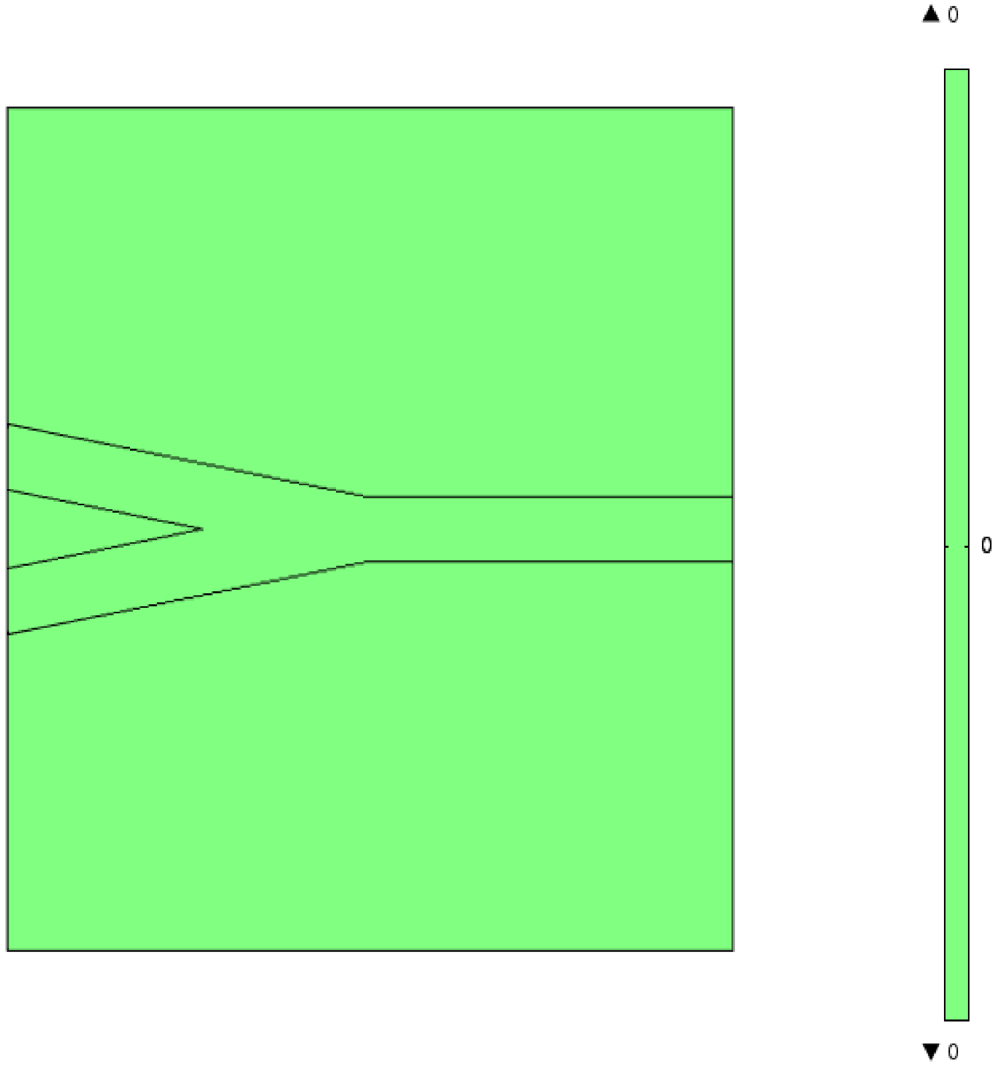

Figure 18 Magnetic Field Obtained When Both the Input Is Off State

When any one of the input ports is ON, 45% of the input power appears at the output. Hence according to the definition of threshold mentioned above output is ON.

Magnetic field are obtained at third port as shown as fig 19.

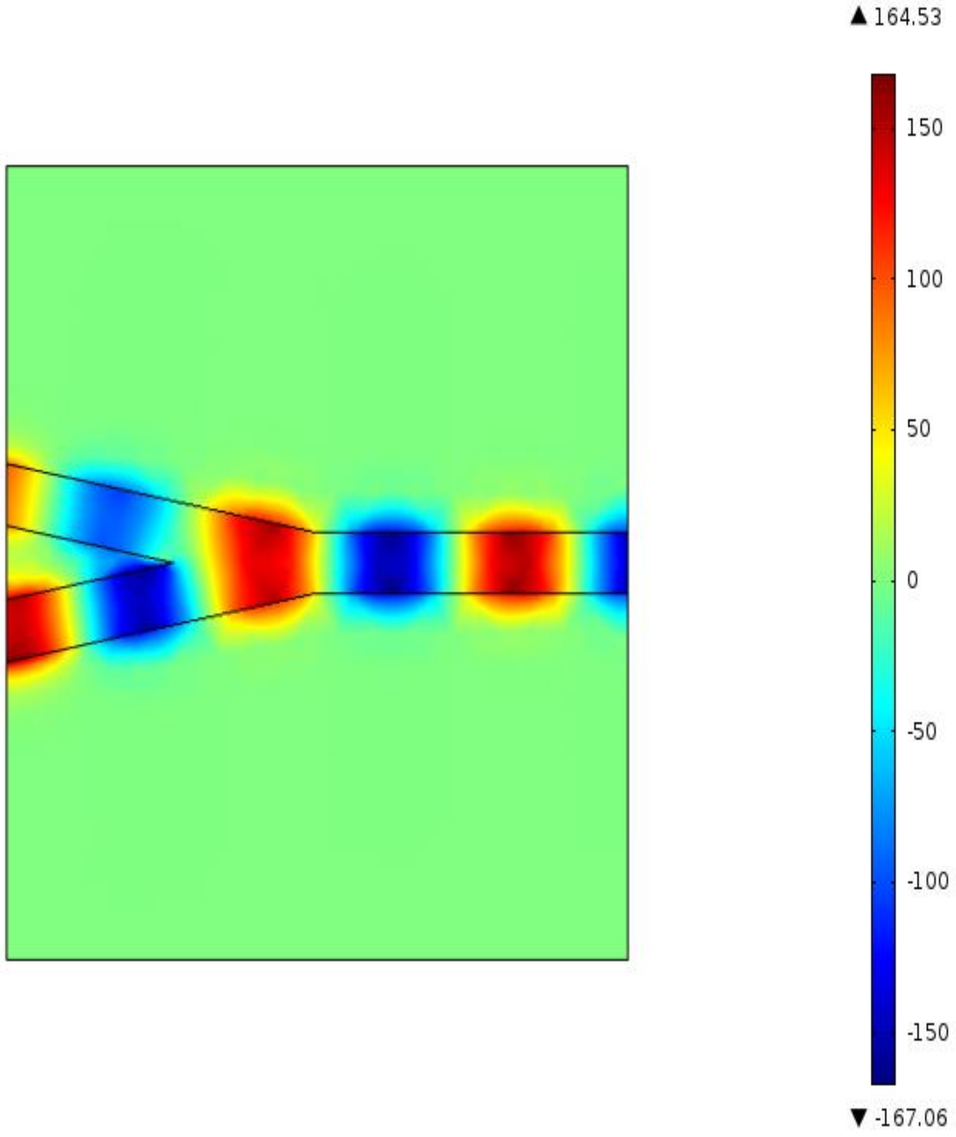

Figure 19 Magnetic Field Diagram Obtained When One Input Is In ON State And Second Input Is In OFF State

In third case, if we give input signal to both of the input ports then we get 185% of input power at the output. This state is also referred as ON state, when both input are ON . When output is greater than 40% it is considered as ON stage and if output is less than 20% it is considered as OFF state.

Magnetic field distributions is shown in fig 20.

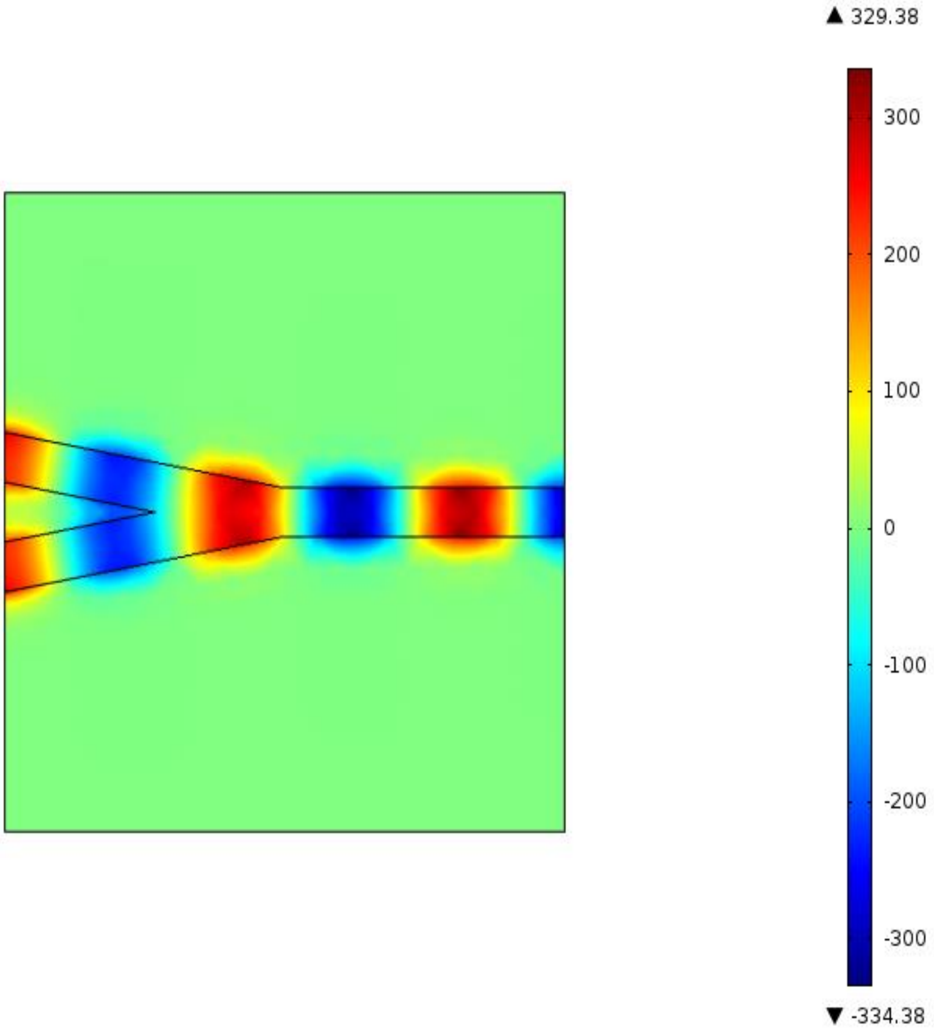

Figure 20 Magnetic Field Obtained When Both The Input At The ON State.

Truth Table for OR gate

A(input 1 port)	B(input 2 port)	C(output port)	P_{Output}/P_{Input}
0	0	0	$P_C/P_A=0$
0	1	1	$P_C/P_B=0.45$
1	0	1	$P_C/P_A=0.45$
1	1	1	$P_c/P_A=1.85$

4.5(c) AND GATE

We have designed an AND gate having three port: two ports are used to input light wave and third port is for the output. This gate has a bit complex geometry made by the fusion of several horizontal and veritical waveguides as shown in figure 21. Length of each waveguide is equal to λ.

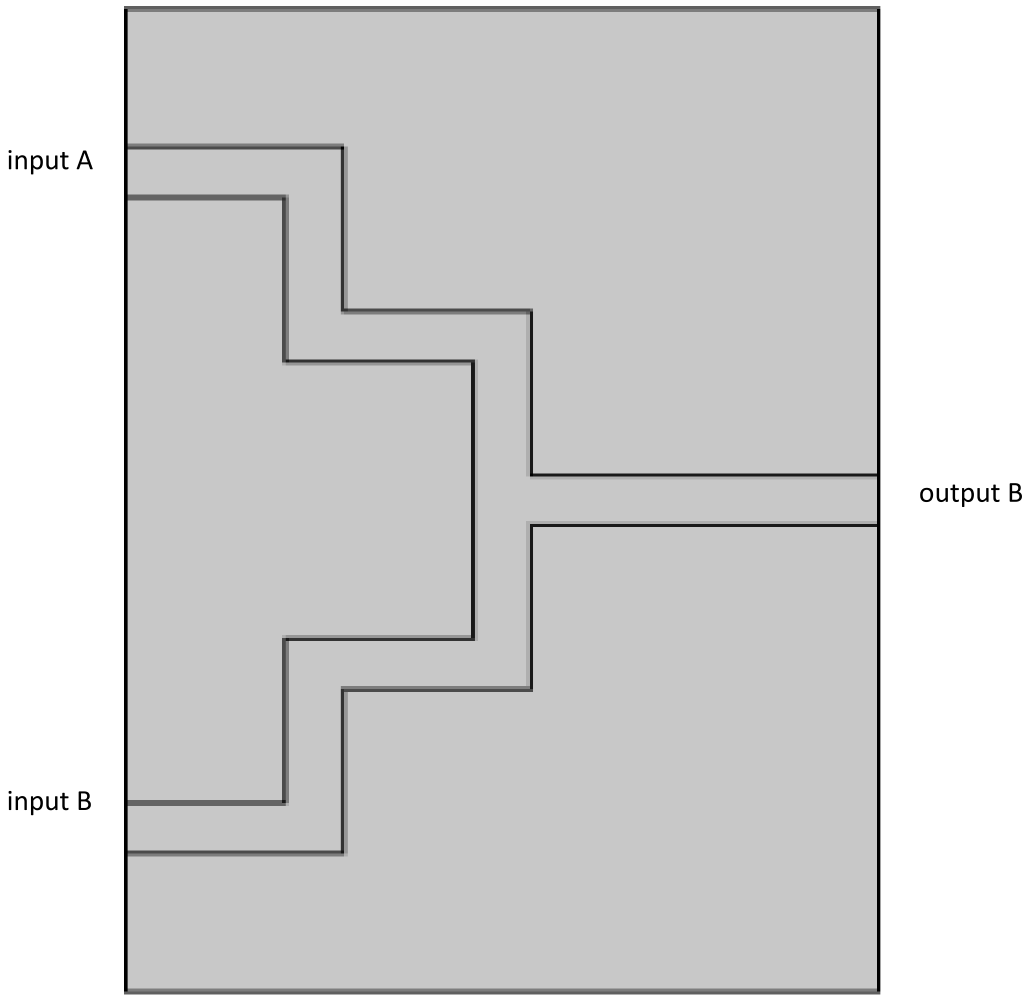

Figure 21 Design Of AND Gate

Input signals are launched at the wavelength of 650nm . When there is no input light wave at either of the input port we get zero at the output port. The magnetic field distribution of this case has been obtained as fig 22

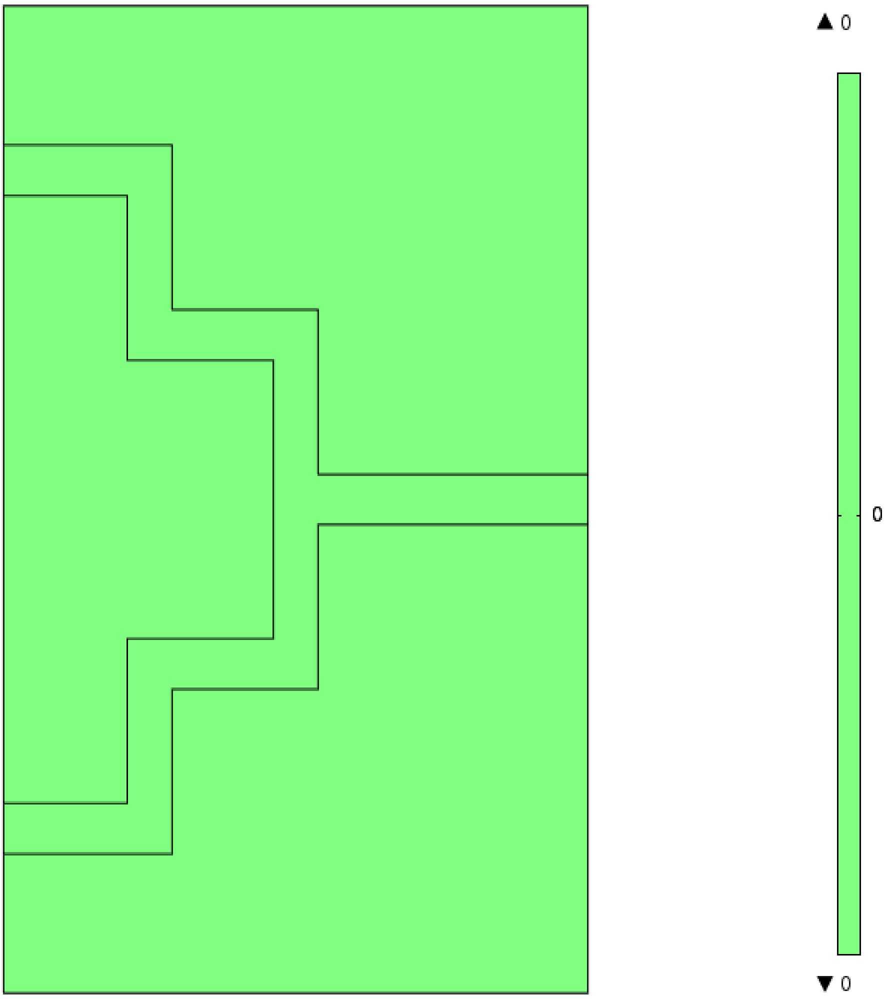

Figure 22 Magnetic Field Obtained When Both The Input Are In OFF State

When we apply input light wave to the any one of the input port and no light wave in the another input port, then we get ~ 20% of the input power as the output. All these above cases are referred as OFF state.

The magnetic field distribution in both the cases is obtained as. Fig 23.

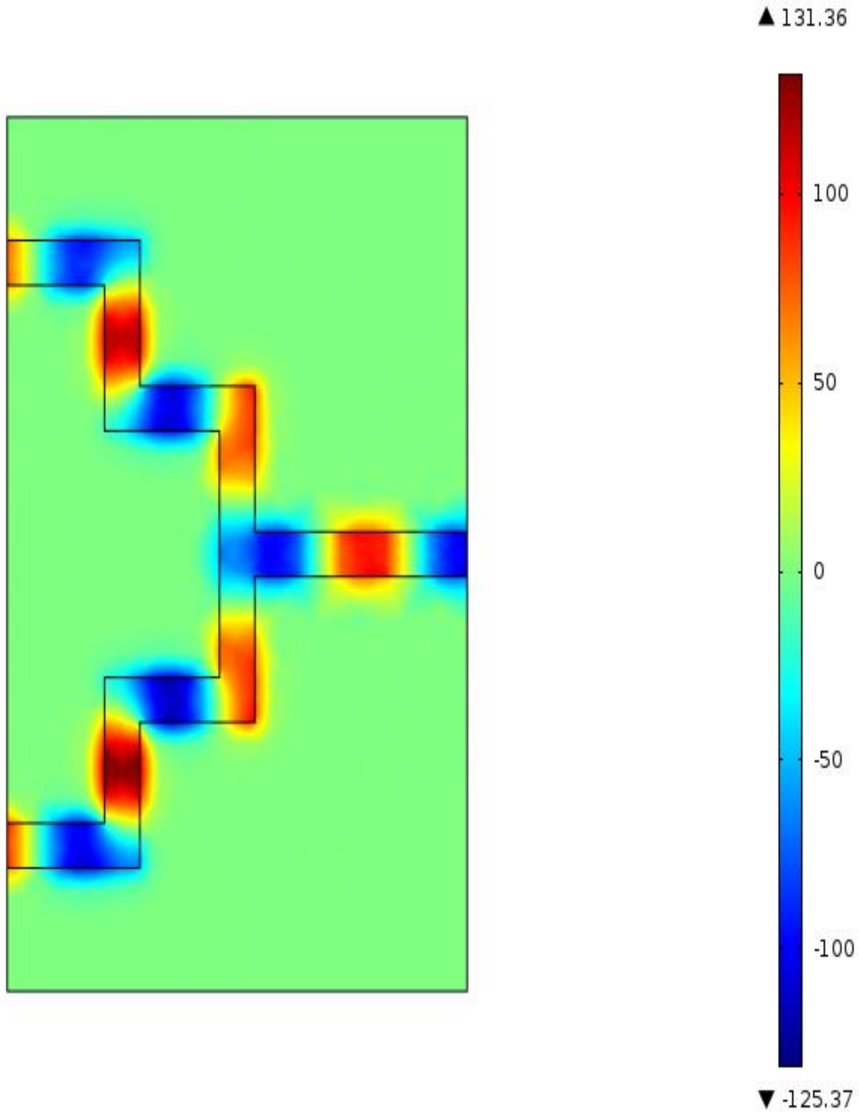

Figure 23 Magnetic Field Obtained When One Of The Input Is In OFF State and Another Output Is In ON State

In another case, if we give input signal to both of the input ports then we get approx 80% of input power as the output. Since we have already defined that when output is greater than 40% it is considered as ON stage and if output is less than 20% it is considered as OFF state.

This state is referred as ON state of the AND gate.

Magnetic field distributions of the ON stage of the AND gate is shown in fig.25

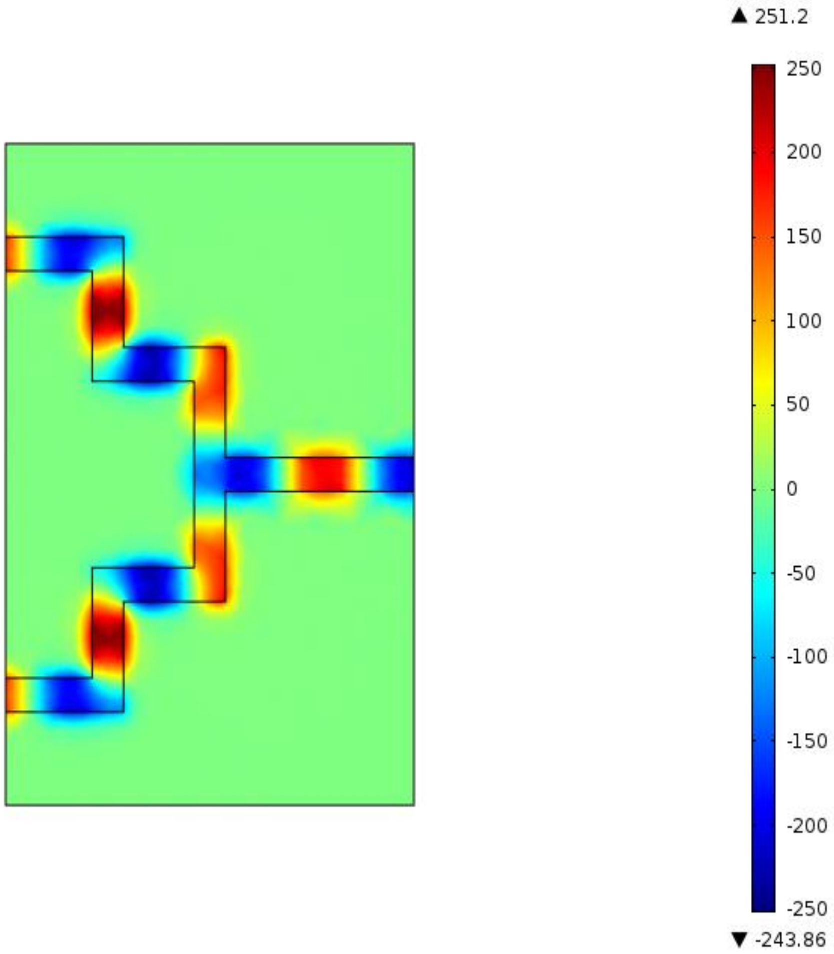

Figure 24 Magnetic Field Obtained When Both The Inputs Are In ON State

Truth table for AND GATE

A(input 1 port)	B(input 2 port)	C(output port)	P_{Output}/P_{Input}
0	0	0	P_C/P_A=0
0	1	0	P_C/P_B=0.19624
1	0	0	P_C/P_A=0.20358
1	1	1	P_c/P_A=P_c/P_A=0.79957

4.5(d) XOR GATE

The design of XOR gate is exactly similar to the OR gate, the only different is the fact that signals at the two inputs have phase difference of 180 degree. The design is shown in figure 25.

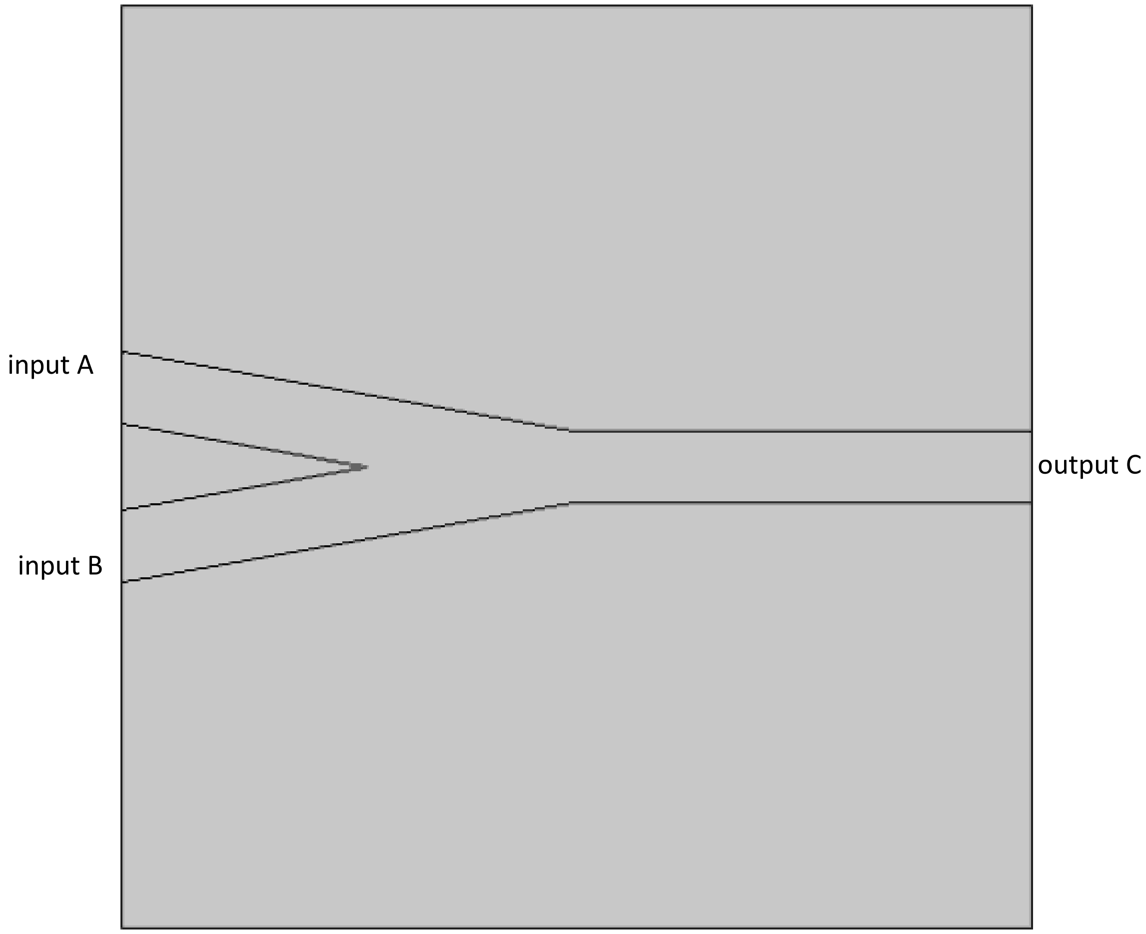

Figure 25 Design Of XOR Gate

Input signals are launched at the wavelength of 650 nm. When both inputs are OFF, output is OFF.

We have obtain magnetic field in this case as fig 26.

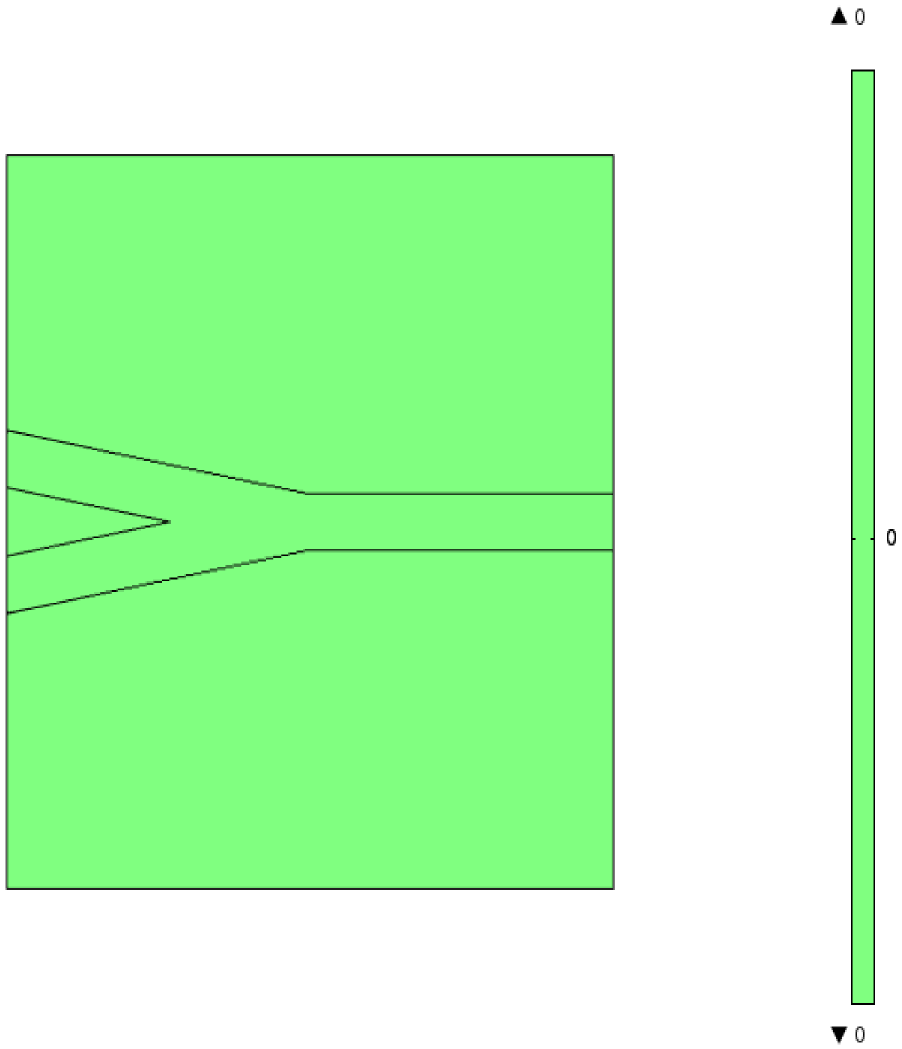

Figure 26 Magnetic Field Obtained When Both the Inputs Are In OFF State

When any one of the inputs is ON keeping the other OFF, ~ 45 % of the input power appears at the output.

The magnetic field obtained as fig 27.

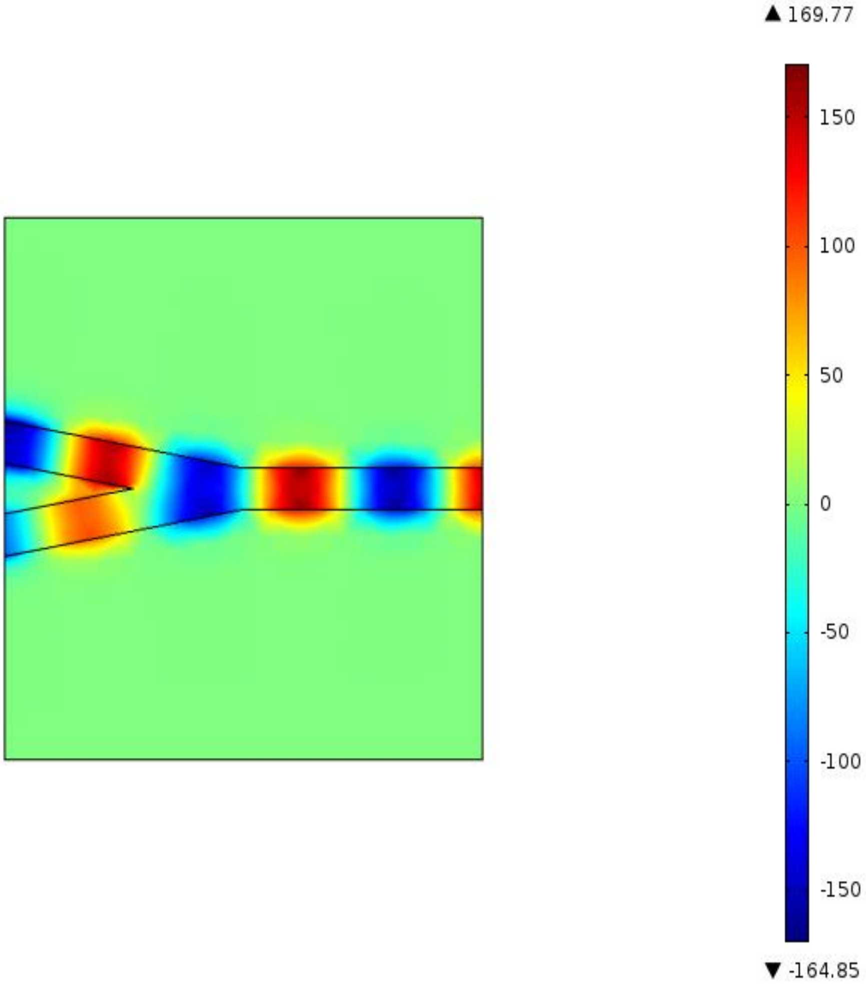

Figure 27 Magnetic Field Obtained When One Of The Inputs Is In OFF State And Other Input Is In ON State

When both the inputs are ON, the signals undergo destructive interfereance and no power is obtained at output port.

Magnetic field in these case obtained as fig 28.

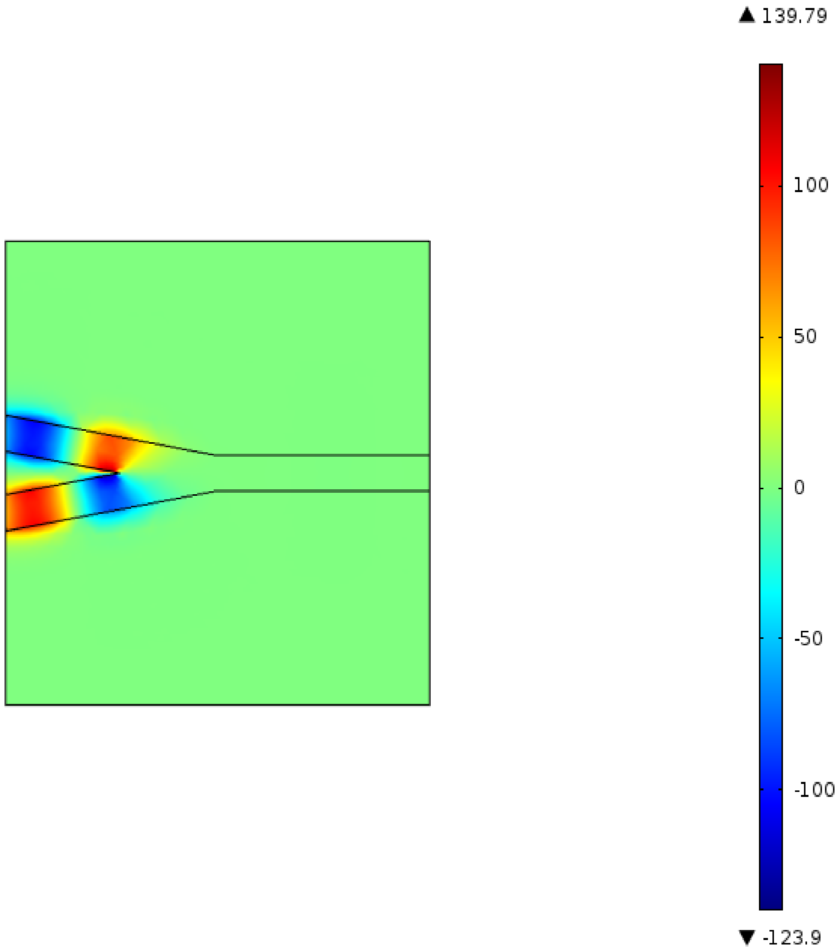

Figure 2**8** When Both Input Are In ON State

Truth table for XOR GATE

	B(input 2 port)	C(output port)	P_{Output}/P_{Input}
0	0	0	$P_C/P_A=0$
0	1	1	$P_C/P_B=0.46091$
1	0	1	$P_C/P_A=0.45956$
1	1	0	$P_c/P_A=P_c/P_A=0.0000234$

Chapter – 5

Conclusions

Plasmonic waveguides based optical AND, OR , XOR, NOT gate has been successfully designed and analysed. Surface plasmon polaritons provide good confinement of power in waveguides of subwavelength thickness. The thickness of the waveguides is 50 nm and chosen wavelength of operation is 650 nm. The proposed optical gates successfully verify their respective truth tables. Threshold values of ON and OFF state have been defined as 40% and 20% of the input power respectively. Which means that, output power is less than 20% of the input power is considered as OFF and greater than 40% of the input power is considered as the ON state. This definition is similar to that of TTL gates. All the proposed structures have been designed while keeping in mind the above mentioned threshold definition. These structures are better than the photonic crystal based logic gates as they free from diffraction limit. Their subwavelength dimension provides the plamonic logic gates an upper hand over the photonic crystal logic gates which are way bulkier.

All optical devices are faster and less lossy compared to electronic and opto-electronics ones. Plasmonic logic gates can make it possible to achieve large scale integration in optical integrated circuits.

Chapter – 6

FUTURE WORK

Work described in this dissertation throws light at the significance of plasmonics in development all optical computing. Though the proposed gates are just the basic ones, they give one a foresight to the possibility of the more complex optical circuits. Some of the novel ideas which should be worked upon in near future are as follows:

- Using the proposed gates, latches, flip flops, half and full adders and subtracters can be developed.
- they can become the basis of nanoscale on-chip antennas and communication circuitry
- if reduced to few nanometers in size, can large scale integration for fabrication of all optical processors.
- Beside insulator-metal-insulator, the metal-insulator-metal waveguide can also be analysed to determine how suitable it is for similar applications.
- Beside SPP, the role of localised surface plasmons (LSP) can also be studies.
- Defect waveguides in and array of metallic scatterers should be studies to develop advanced and low loss versions of the proposed logic gates.

All optical gates can make way for the fabrication of ultra-high speed optical microprcessors for computing and communication purposes.

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