Performance Analysis of All-optical Logic Gates Based on Cross-phase Modulation in an Asymmetric Coupler

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DECLARATION

I, Abha Aggarwal, hereby declare that the work, which is being presented in this dissertation entitled "Performance Analysis of All-optical Logic Gates Based on Cross-phase Modulation in an Asymmetric Coupler" by me in partial fulfilment of the requirements for the award of degree of Master of Engineering in Electronics and Communication Engineering from Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Dr. Hardeep Singh.

I have not submitted the matter presented in the thesis for award of any other degree of this or any other university.

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ABSTRACT

The importance of fiber optic communication is increasing at very fast pace in today’s world. The demand for transmission in broadband internet services for data transmission like real time video conferencing and in telecommunication network over the globe is growing at an exponential rate and only fiber optics communication networks are able to meet this challenge. Optical fiber communication systems are being extensively used all over the world for telecommunication, video and data transmission purposes. This is because of the huge capacity of optical fiber. It can provide data rates in Tbps over optical fiber by wavelength division multiplexing techniques.

Switching function is very important in information processing in optical networks. The recent trend is to design All optical network elements in optical signal processing which eliminate use of costly high speed electronics because they don’t need optical to-electronic-to-optical' conversion.

In our thesis work, we investigated Nonlinear Fiber Directional Coupler which has technological applications in power splitting, wavelength division multiplexing, demultiplexing, polarization splitting and fiber optic sensing. We analyzed the switching characteristics of nonlinear directional fiber coupler in presence of Kerr nonlinearity. We introduce a pulse into the nonlinear directional coupler, and add a pump light by wavelength division multiplexing which is to use Kerr effect as an advantage and produce the cross-phase modulation. We then analytically solve the coupled nonlinear Schrodinger equations for the input power and plot transmission coefficient with respect to normalized input power for varying values of coupling coefficient. After that, we analyse the effect of coupling coefficient on the switching characteristics i.e. transmission coefficient with respect to normalized input power with input signal in one port and input signal in both the ports respectively.

We analyse that by increasing the value of coupling coefficient K, the maximum value of transmission coefficient for core 1 decreases and the minimum value of transmission coefficient for core 2 increases and by increasing the value of K, the input power for peak value of transmission coefficient also increases. We also observe that by increasing the value of coupling coefficient from 0.05 to 0.1 the graphs for pump power $p_p< 1$ and $p_p> 1$ are reversed. We study the effect of different values of gain of core 1 and core 2 on the extinction ratio. It can be seen that an OR gate, a XOR gate and a new logic expression D = $\bar{A}.B$ has been realized.

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CHAPTER 1

Introduction

1.1 Optical Switching Systems

The switching function is one of the important functions of all information processing and information transmission systems. Most of them such as communication networks or computers consist of connected switches. Maximum communication apparatus is set up on electrical pulses, which means that the light pulses have to be transformed to electronic signals, intensified, renewed, and then again transformed to light pulses. This is usually denoted as an 'optical-to-electronic-to-optical' (OEO) alteration and is a substantial tailback in broadcasting of data. The large amounts of data propagating all over the optical system is essential to be swapped through numerous points acknowledged as nodes. The optimum approach to move the signal is to first spot the optical signal from the input optical fiber, transform it to an electronic pulse, and then change back to an optical pulse, which is then directed to the optical fiber we need the signal to go to. In a long-haul communication network, an OEO conversion might be needed each 600 kilometres only for doing strengthening. The biggest advantage of optical switching is that by exchanging current electrical switches with optical switches, the requirement for OEO conversions is eliminated. The benefits are highly important. The very first is Optical switches are cheaper and there is no need of costly high speed electronic devices. The removal of complexity also makes smaller optical switches. The vital simplification of optical systems would be a possible chance to avoid multiple conversions of signals from an optical to electrical form to provide switching. All optical switching devices can help in accomplishing this task. Mostly, all optical switching takes place when output characteristics of device can be determined by parameters of input pulse or by a separate controlling signal. The optical switching could be done by plenty of devices, one of these devices are those in which switching operation relies on the optically controlled power exchange between two nodes guided in an integrated optics or fiber systems. Another type of devices relies on changes in phase difference between two input signals that are generated optically. A significant device which can perform all optical switching is fiber coupler

1.2 Directional Couplers

Directional couplers are passive structures that are often utilized in the area of communication and networking. They transfer fixed quantity of the electromagnetic power in a transmission line to another transmission line which enables the power to be utilized in a different device. A salient characteristic of directional couplers is that they are unidirectional. Power entering in the output port is transferred to the isolated port.

The basic construction of couplers includes two transmission lines placed nearby each other so that power entering in one transmission line is transferred to another. The devices operating at microwave frequencies commonly use this technique. At lower frequencies, lumped component devices are also possible. Also, waveguide designs can be used at microwave frequencies, particularly the higher bands. Most of these guide couplers are related to one of the transmission line schemes, however there are some designs which are exclusive to the guide.

Directional couplers have wide number of uses, which are; provoked the signal sample for measurement or monitoring, the output signal again fed into input i.e. feedback, combination of feeds to and from the antennas, provision of taps like cable TV, antenna beam formation and separation of transferred and received signals on cellular phone lines.

The symbols used for the couplers are as displayed in figure 1.1. The sign noticeable on it denotes the coupling factor of the directional coupler. These couplers consist of four ports. Port 1 is called the input port from where the power enters. Port 3 is called the coupled port where some part of the power inputted to port 1 is coupled. Port 2 is called the transmitted port where the signal from port 1 is outputted, minus the part that goes to port 3. The couplers are often not asymmetrical so there is a port 4, called the isolated port. A part of the power entering port 2 will be transferred to port 4. But, the coupler is not frequently utilized in this way and port 4 is often ended with a matched load. This can be done within the circuit and port 4 is not available for use. This leads to a 3-port device, therefore the importance of the additional notation for directional couplers in figure 1.1.

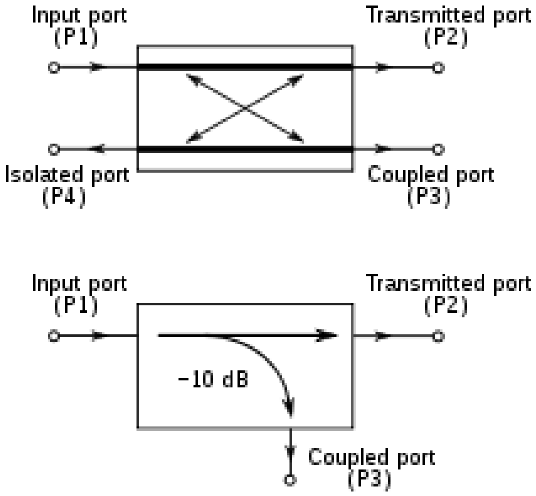

Figure 1.1 Two symbols used for directional couplers

1.3 Coupled Transmission Lines

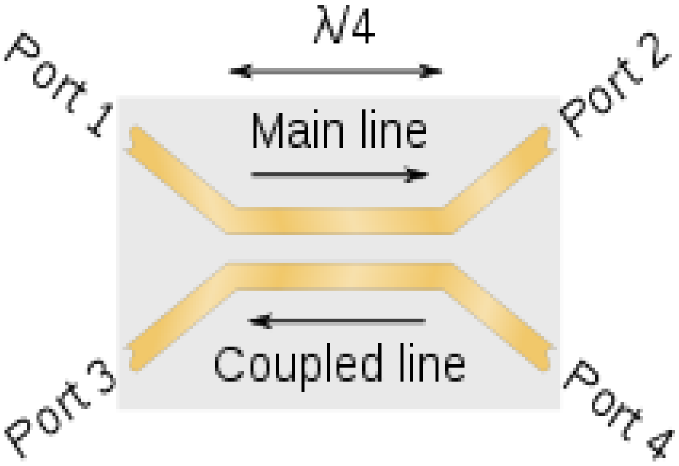

Figure 1.2 Single section λ/4 directional coupler

The utmost basic and known arrangement of directional coupler is a set of parallel transmission lines placed close to each other. A number of technologies that can be used to realise directional coupler include coaxial and the planar technologies (stripline and microstrip). Figure 1.2 shows an execution in stripline of a quarter-wavelength (λ/4) directional coupler. The signals in the coupled line flow in the reverse direction to the signal in the main transmission line. That is why it is occasionally known as a backward coupler.

The term main line denotes the fragment between ports 1 and 2 and coupled line to the fragment between ports 3 and 4. Since the output varies as a linear function of the input in the coupler, the symbols on figure 1.2 are random. Any of the four ports can be the input port, which makes the directly connected port the transmitted port, the neighbouring port being the coupled port, and the opposite port of the coupled port is the isolated port. In a few directional couplers, the main transmission line is used for high power operation and the coupled port is designed for a small connector, for example an SMA connector. The internal load power value might decrease the required operation on the coupled line.

Parameters

Common properties desired for all directional couplers are high directivity, wide operational bandwidth and a good impedance match when the port are clear in matched load. Some characteristics of impedance mismatch are explained below.

Coupling factor

The coupling factor is defined as: C = 10 log $(\frac{P_3}{P_1})$ dB

where P_1 is the input power at port 1 and P_3 is the output power from the coupled port.

The directional coupler is important for coupling factor. Coupling coefficient is always negative, it cannot be greater than 0 dB for a inactive device, and practically does not surpass −3 dB as greater than this will give more power in case when coupled port is used. Coupling is variable and differs with frequency. Diverse schemes decrease the change but a without a glitch flat coupler is ideally not possible.

Loss

The insertion loss from port 1 to port 2 ($P_1 - P_2$) is:

Insertion loss: $L_i = -10\log\left(\frac{P_2}{P_1}\right)\ dB$

Some of this loss is due to a portion of power entering in the coupled port and is called coupling loss and is given by:

Coupling loss: $L_c = -10\log\left(1 - \frac{P_3}{P_1}\right)\ dB$

The insertion loss is an ideal case of directional coupler that produce coupling loss. In a practical directional coupler, the insertion loss is a mixture of conductor loss, coupling loss, dielectric loss and VSWR loss. Based on the frequency range, coupling loss becomes a bit less severe above 15 dB . At 15 dB coupling the losses are equal to total loss.

Isolation

Isolation of a directional coupler is known as the difference in input power and output port power in dB and expressed as:

Isolation: $I_{4,1} = -10 \log\left(\frac{P_4}{P_1}\right)$ dB

Isolation is also calculated between the output ports. In such a situation, one among the two output ports is utilized as the input port; the other port is taken as the output port and the remaining two ports are ended by matched loads.

$I_{3,2} = -10 \log\left(\frac{P_3}{P_2}\right)$ dB

The isolation between the input and the isolated ports can be different from the isolation between the two output ports. The isolation between ports 1 and 4 can be 30 dB but the isolation between ports 2 and 3 may be a different value like 25 dB. Isolation can be approximated by coupling added by return loss. The isolation value should be as large as possible. In practical couplers the isolated port is never wholly isolated. Some RF signals will always be present. Waveguide couplers will have the best isolation.

Directivity

Directivity is directly related to isolation. It can be defined as:

Directivity: $D_{3,4} = -10 \log\left(\frac{P_4}{P_3}\right)$ dB

where P_3 is coupled port that is output power and P_4 is the isolated port.

The directivity should be as large as possible. The directivity is very large at the design frequency and is a function of frequency because it is proportional to the cancellation of two wave components. Waveguide couplers will have the best directivity. Directivity can be directly calculated, and is defined as difference between isolation and coupling defined as:

$D_{3,4} = I_{4,1} - C_{3,1}$ dB

Amplitude balance

This term is equal to the power difference between the two output ports of a 3 dB hybrid circuit in dB. In an ideal hybrid device, the difference must be equal to 0 dB. But, in a real circuit the amplitude balance is frequency dependent and wavers from the perfect 0 dB change.

Phase balance

The phase change occuring between the two output ports will be 0°, 90°, or 180° in case of hybrid depending on the type of coupler that is used. But, like amplitude balance, the phase change is affected by the input frequency and it would fluctuate a few degrees.

1.4 Non-linear Shrodinger Equation

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} = i\gamma|A|^2 A - \frac{\alpha}{2}A$$

where fiber losses are included through the α parameter while β_2 and β_3 account for the second- and third-order dispersion (TOD) effects[1].The nonlinear parameter $\gamma = 2\pi\, n_2/(\lambda\, A_{eff})$ is defined in terms of the nonlinear-index coefficient n_2 , the optical wavelength λ , and the effective core area A_{eff}.

1.5 Coupled Mode Devices

We know that there is an evanescent field extending outside any dielectric waveguide. If two waveguides are placed sufficiently close together, these parts of the field must overlap spatially. Mostly, the required interwaveguide gap for this overlap to be significant is of the order of the guide width. For example, Figure 1.3 shows the situation for the lowest-order modes in two identical, adjacent symmetric slab waveguides. The refractive index profile of the twin- guide system is also shown. The indices of the two guide cores are n_{g1} and n_{g2}, respectively, and the index in the substrate material outside the guide has the uniform value n_s.

Because of the intermodal overlap, it is not easy to decide which waveguide any light in the overlap region really belongs to. This implies that there must be a procedure for light in one guide to be transferred to the other. It turns out that, if the two waveguides satisfy a particular set of conditions, and are close to each other for a required distance, this exchange of power can be highly significant, reaching almost 100% in most cases. The optical signal then starts coupling back, so the power to be transferred must be periodic with distance. This is shown in Figure 1.4.

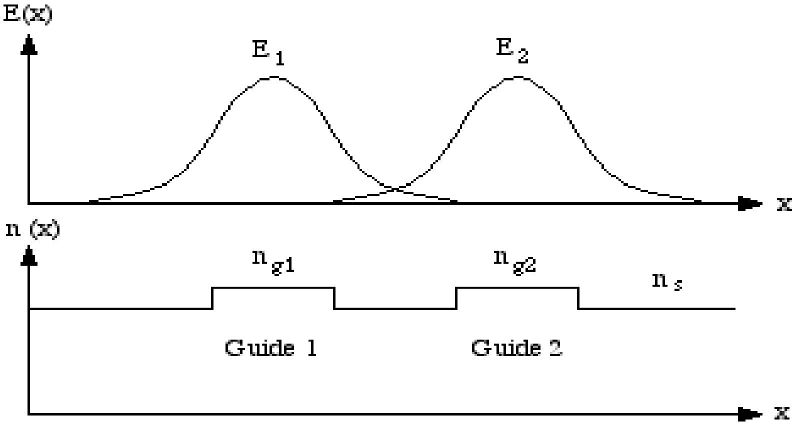

Figure 1.3 Overlap of the transverse fields of two adjacent parallel symmetric slab guides

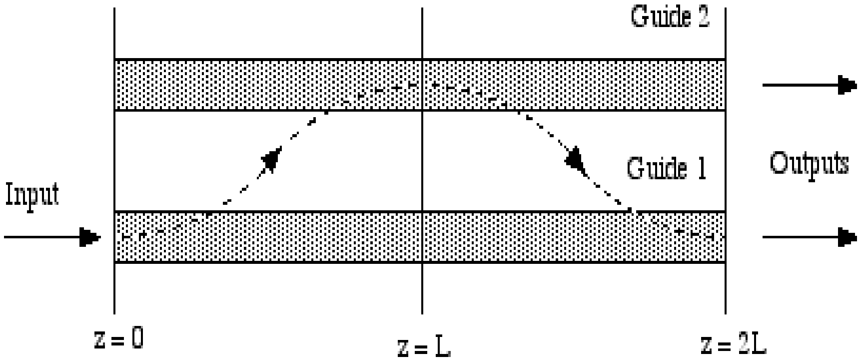

Figure 1.4 Conceptual representation of the coupling process[2]

1.6 Optical Switching

Switching is an important and essential feature in telecommunications, which can be explained in two parts: a higher level that requires advanced electronics and the physical level consisting of components and devices that “switch” signals within the communication network. Only devices at the physical level can be “all-optical”, and also discuss component of different types of all-optical switching that are present or are evolving for switching functions. In practical scenario, many optical switches are optoelectronic, with light signals converted to electrical form for switching, and the electrical signals then operating an optical transmitter. All-optical switches switch signals in the form of optical signals, either by reassembling all light signals in a fibre or in WDM system by choosing signals at certain wavelengths. Some switches can separate individual wavelengths, but typically their input is an individual optical channel that was previously separated from other channels by a de-multiplexing system which means they function at the optical-channel level, without any concern to what information the optical channel is transmitting. Electronic or optoelectronic switches are required to perform operations on the data that is transmitted on each channel, such as TDM transmit signal in the time slot for long distance transmission. One further difference is between “transparent” and “opaque” optical switches. The most current are transparent all-optical switches, since they transmit the light signal, without converting it into some other form. One example is a moving-mirror switch that distributes the input light in many directions. Opaque switching convert the light signals into some other form, and so they do not transmit them exactly as they were received. They consist of optoelectronic types that transform different wavelength of signal by using optical or electronic techniques.

Optical Switch Parameters

The parameters related to an optical switch are as follows:

1. Switching time – The most important feature of a switch. It must be known that different applications have different switching time requirements.

2. Insertion Loss – The fraction of a signal power introduced by the switch. It is measured in dB and must be as low. The insertion loss is same for all input and output switches, this is known as loss uniformity.

3. Crosstalk – The ratio of power at a specific output from the desired input, to the power from all other inputs.

4. Extinction Ratio – The ratio of power in the on-state to the power in the off-state of input-output. This should be as high as possible.

5. Polarization dependence loss (PDL) – Measured loss of the switch due to the different losses observed in the two states of polarization. It is required that optical switches have low PDL.

6. Reliability – The ability to perform the desired switching operation after 'a million' of cycles. The reliability is also a measure of the switching capability after the switch remaining untouched for a long period of time.

7. Energy usage – Power consumption of the switching device.

8. Scalability – The ability of a switch to have large port counts that perform adequately.

9. Temperature resistance – The switch ability to maintain the desired behaviour facing temperature changes.

Types of optical switches

An optical switch is a simple switch which accepts an optical signal at one of its input ports and at receiver sends signal to other port used the decision of the routing algorithm. There are two basic types of optical switching methods**.** There is the all-optical switch (OOO) in which the switching fabric is made purely through photonic means, and electro-optical switch (OEO), which requires the analog light signal to be converted to a digital one first and then processed and routed, and then converted back to the analog light signal. These switches can be seen below.

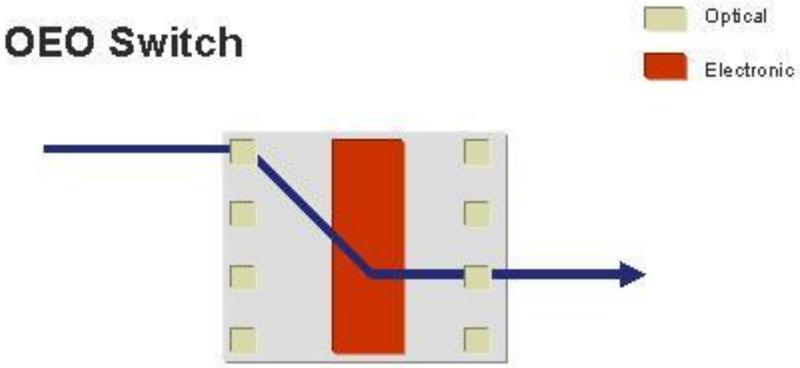

Figure 1.5 All-optical Switch

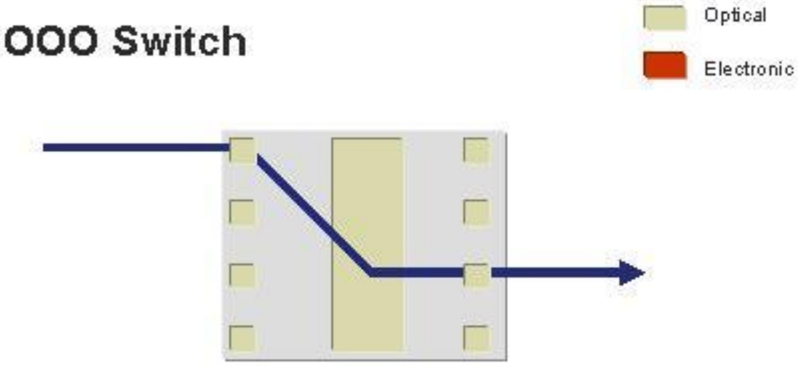

Figure 1.6 Electro-optical Switch

There is a futuristic vision where an All Optical Network (AON) could become a reality. An AON will be switched, transported and managed all at an optical level. So, this will result in it being less expensive and faster than our present optical communication network with electrical parts. But, our present technology is not sufficiently sophisticated for this to take place. While we wait for our technology to advance, we should continue using OEO switching. Both technologies have their own merits but question arises how they both can used.

The OEO switch is used in telecommunication today. The disadvantage of this technology is that it might not be able to cope with the rate of transmission in the coming days. Although it is not a disadvantage today, the amount of data transmitted is growing rapidly as the ability to switch it.

1.7 Motivation

Optical fiber technology has revolutionized the world of communication by providing high speed data and video transmissions. It is possible because of huge bandwidth of optical fiber. Switching is very important operation in signal processing of optical communication. Waveguide couplers are used to perform various signal processing functions like switching, power splitting and fiber optic sensing. The recent trend in optical communication is to switch towards all optical devices which eliminate costly high speed electronics and optical-electrical-optical conversion which is quite complex. The motivation behind this work is to explore nonlinear directional fiber coupler which is an all optical device and makes use of fiber nonlinearities for its operation .It consists of two closely placed optical fibers which results in overlapping modal fields. It has applications in switching and all signal processing functions like to design all optical logic gates.

1.8 Objectives

1. To investigate the performance of nonlinear directional fiber coupler in presence of cross-phase modulation

2. To study the switching characteristics and maximize the transmission factor by varying the input pump power

3. To design logic gates of optical fiber coupler for efficient switching operation

1.9 Outline of Dissertation

The Dissertation is organized in 5 Chapters

Chapter 2 describes various Linear and Nonlinear effects in optical fiber used in fiber coupler and their effects on optical pulse propagating through fiber.

Chapter 3 gives literature survey related to our work.

Chapter 4 describes soliton switching in Nonlinear Fiber Directional Coupler in presence of cross-phase modulation.

Chapter 5 describes conclusion and future scope of our work

CHAPTER 2

Nonlinear Effects in Fiber Coupler

2.1 Kerr Effect

The Kerr effect is an optical effect which occurs when high intensity light passes through optical medium. This effect happens due to nonlinear polarization in the medium due to light intensity and itself modifies the propagation of light .It can be described as the change in refractive index of medium by change in intensity of optical signal. The refractive index changes according to

$$\Delta n = n_2 \mathrm{I}$$

Where n_2 is nonlinear refractive index and I is optical intensity. This effect is responsible for various nonlinear phenomenon like self-focussing, Self-phase modulation and modulation instability.

2.1.1 Self-phase Modulation

SPM is caused by variations in the power intensity of an optical signal and leads to in distinctions in the phase of the signal. It leads to the spectral broadening of pulses. Signal bandwidth is increased due to effect of SPM (self-phase modulation), it also change phase of the signal. Self-phase modulation has stimulated many applications in the field of ultrashort pulse including to cite a few:

- spectral broadening and supercontinuum
- temporal pulse compression
- spectral pulse compression

In long-haul single-channel and DWDM systems SPM is one of the most important reach limiting nonlinear effects. It can be reduced by:

- Lowering the optical power at the expense of increased noise

- Dispersion management, because dispersion can partly mitigate the SPM effect

2.1.2 Cross-phase Modulation

CPM occur when wavelength of one channel change the phase of the other channel. It leads to spectral broadening of pulses. Large effective-area fiber (LEAF) has been developed for reducing fiber nonlinearities. Cross-phase modulation can be used as a method for adding data to a light stream by varying the phase of a coherent optical ray with another ray through contacts in an suitable non-linear medium. This procedure is useful to fiber optic communications. In DWDM applications with intensity modulation and direct detection (IM-DD) the influence of XPM is a two-step process: Initially the signal is phase modulated by the co-propagating second signal. In a second stage dispersion leads to a conversion of the phase modulation into a power variation. Furthermore the dispersion leads to a walk-off between the channels and thus lessens the XPM effect. The phase shift for a particular channel relies depend both of the channels power [3]. The jth channel phase shift is defined as:

$$\emptyset_j^{NL} = \frac{\gamma}{\alpha}\left(P_j + 2\sum_{m\neq j}^{N} P_m\right)$$

where the first term is due to SPM and L_{eff} has been replaced with 1/α assuming αL ≫1. The parameter γ is in the range 1–10 $W^{-1}km^{-1}$ depending on the type of fiber used. For DCF the value of γ is very large. The phase shift depend on channel power, order of the channel and its value is vary from zero to maximum i.e.$\emptyset_{max}$ = (γ / α)(2N − 1) P_j for N channels, if we assume equal channel powers.

The XPM-induced phase shift should not upset system performance if the GVD effects were small. Though, a little dispersion in fiber changes pattern-dependent phase shifts to power fluctuations, decreasing the SNR at the receiver. This change can be understood by observing that time-dependent phase fluctuations result in frequency chirping that disturbs broadening of the signal. Figure 7 shows for 10gb/s of pump channel XPM-induced.

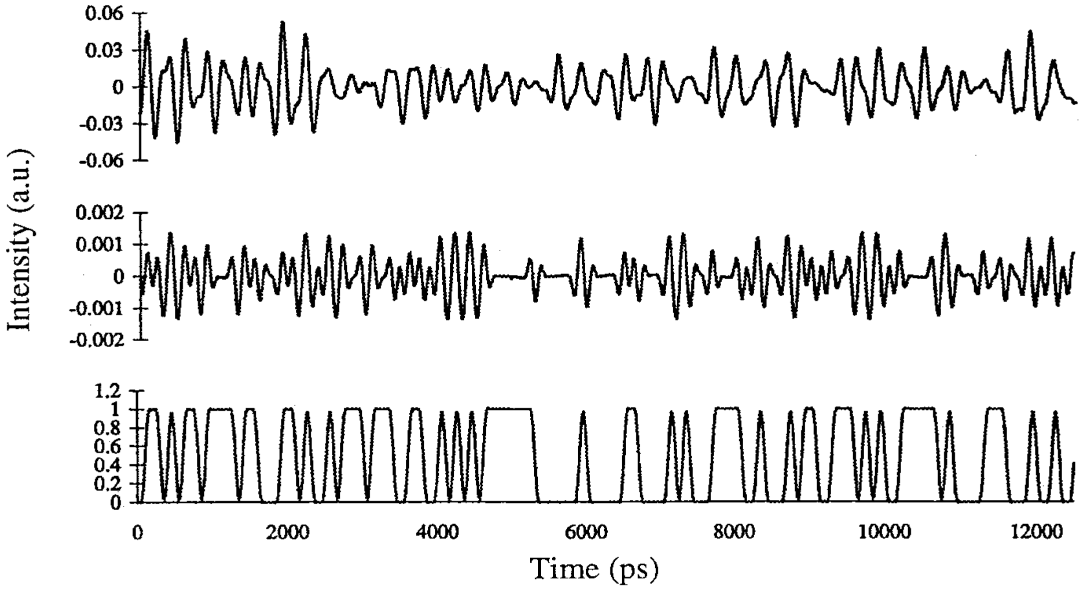

Figure 2.1 XPM-induced power fluctuations [4]

2.1.3 Four Wave Mixing

When three frequencies (f_1, f_2 and f_3) pass through a nonlinear medium, a fourth wavelength (f_4) is generated. Three inputs frequencies f_1, f_2, and f_3 are given, the nonlinear system will generate

$$f_4 = \pm f_1 \pm f_2 \pm f_3$$

with the utmost harmful signals to system performance calculated as

$$f_{ijk} = f_i + f_j - f_k, \quad \text{where i, j} \neq k$$

Four-wave mixing also exists if only two constituents interact. In this situation the term

$$f_0 = f_1 + f_1 - f_2,$$

couples three components, therefore producing degenerate four-wave mixing, showing similar properties as in instance of three interacting waves.

FWM is a nonlinear effect in optical fiber communication that affects wavelength-division multiplexing (WDM) systems, where multiple wavelengths are spaced at equal intervals or have equal channel spacing. The effects of FWM increase with decreased channel spacing and at high power levels. Increased chromatic dispersion decreases FWM effects, as the pulses lose coherence. The intervention FWM instigated in WDM systems is called interchannel crosstalk. FWM can be reduced by using random channel spacing or fiber that enhances dispersion.

2.2 Stimulated Light Scattering

Rayleigh scattering is type of elastic scattering in which frequency of scattering light is unchanged on passes through the fiber. The frequency shift in Rayleigh is downward. Two other type of scattering are stimulated Raman scattering and Brillouin scattering [5]. The main difference between the two is that optical phonons contribute to Raman scattering, whereas acoustic phonons contribute to Brillouin scattering. In Raman scattering frequency shift occur in both direction but in Brillouin frequency shift occur in backward direction. In Brillouin scattering the light is scattered in reverse direction. The threshold power in SRS is 1 w which is higher than SBS.

2.2.1 Stimulated Raman Scattering

Spontaneous Raman scattering arises in optical fibers when a pump wave is deviated from a straight trajectory by the molecules of silicon material [1]. Figure 8 shows the energy level diagram. Energy transfer from higher to lower is called stoke wave and it lose their energy. The photon transfer their energy from lower state to higher state called pump power and it gain energy. Raman shift is defined as $\Omega_R = w_p - w_s$. Since a sound wave is not convoluted, spontaneous Raman deviation from a straight trajectory is an isotropic process and takes place in all directions.

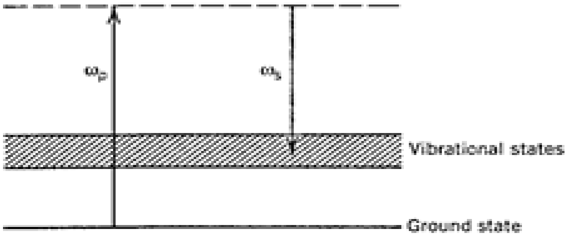

Figure 2.2 Energy levels participating in the SRS process [6]

2.2.2 Stimulated Brillouin Scattering

In the presence of electric field SBS phenomenon occur [5]. For an oscillating electric field at the pump frequency Ω_p, this process creates a sound wave at some frequency Ω. Spontaneous Brillouin scattering can be seen as deviation of the pump wave from a straight trajectory from this sound wave, it create pump frequency of Ω_s. The energy requires that the Stokes shift Ω equals $w_p - w_s$.

2.3 Quintic Nonlinear Effect

The quintic nonlinearity is higher order nonlinearity in optical fiber dynamics. When the Fiber coupler is fabricated with semiconductor-doped fibers, it is not sufficient to analyse only Kerr nonlinearity to study dynamics of system as quintic nonlinearity will comes into play. The quintic nonlinearity could be focussing or defocusing type .the focussing effect will help Kerr nonlinear effect while defocusing effect acts opposite to Kerr nonlinear effect. In our study we consider defocusing quintic nonlinear effect.

2.4 Third Order Dispersion

The pulse broadening due to the dispersion is according to GVD term proportional to β_2 in NLSE. Although term dominates in most of practical system, it is sometimes necessary to include the third-order dispersion (TOD) governed by term β_3. For example, if the signal wavelength coincides with the zero-dispersion wavelength λ_D and $\beta_2 \approx 0$, the third order dispersion provides the dominant contribution to group velocity dispersion in this case. For ultra-short pulses with width $T_0 < 1$ ps, it is necessary to include the term β_3 because parameter $\Delta\omega/\omega_0$ is no longer small enough to justify the truncation of the terms in derivation of nonlinear Schrödinger equation after the β_2 term. The dispersion factor would become

$$\frac{\partial A_2}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 A_1}{\partial t^2} - i\frac{\beta_3}{6}\frac{\partial^3 A_1}{\partial t^3}$$

Where is third order dispersion factor.

2.5 Intrapulse Raman Scattering

In the case of optical fibers, the intrapulse Raman scattering is very important for ultra-short pulse with pulse width (T_0 < 1ps) and must be considered in study pulse propagation of optical pulses of very small width. During propagation the high frequency components of signal pump the low frequency components of the same signal by stimulated Raman scattering thereby transferring energy to low frequency components as pulse spectrum shifts the pulse speed decreases due to group velocity dispersion. The following effects are observed

1. Shift in pulse position in time.
2. Raman-induced frequency shift (RIFS) in the pulse spectrum towards longer wavelengths.

2.6 Self-Steepening Effect

Self-steepening is higher order nonlinear effect and it becomes very important to consider for optical pulses of pulse width (T_0 < 1ps) .It produces temporal and spectral shift during pulse propagation. It can produce temporal shifts even when Raman coefficient is equal to zero.

2.7 Modal Field Diameter

The Mode Field Diameter (MFD) in single mode fiber is the section of fiber where the most of the light energy propagates along the distance. It is generally greater than the actual core diameter (i.e. if the core diameter is 8um the MFD is 9.5). It is larger than core diameter because some of the light energy travels through the cladding**.**

2.8 Nonlinear Schrodinger Equation

To describe the propagation of light signals in optical fibers nonlinear schrodinger equation is used. To derive it, electromagnetic wave model is used. We know the Maxwell equations in absence of free charges as in case of optical fiber, we have

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{1}$$

$$\nabla \times H = \frac{\partial D}{\partial t} \tag{2}$$

$$\nabla . D = 0 \tag{3}$$

$$\nabla . B = 0 \tag{4}$$

Taking curl of (1) we get

$$\nabla \times \nabla \times E = \nabla \times \left(-\frac{\partial B}{\partial t}\right) = -\frac{\partial}{\partial t}(\nabla \times B)$$

$$\nabla \times \nabla \times E = -\mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2} - \mu_0 \frac{\partial^2 P}{\partial t^2}$$

Using mathematical identity

$$\nabla \times \nabla \times E = \nabla(\nabla . E) - \nabla^2 E$$

We have $\nabla . E = 0$ and $1/\mu_0 \epsilon_0 = c^2$

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \mu_0 \frac{\partial^2 P}{\partial t^2} \tag{5}$$

$$P = \epsilon_0\left(\chi^{(1)}.E + \chi^{(2)}.E.E + \chi^{(3)}.E.E.E + \cdots\right) = P_{LIN} + P_{NONLIN}$$

In this equation $\chi^{(2)}.E.E$ is very small and can be neglected for SiO_2 and $\chi^{(3)}.E.E.E$ term corresponds to nonlinearity.

Now (5) becomes

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \mu_0 \frac{\partial^2 (P_{LIN})}{\partial t^2} + \mu_0 \frac{\partial^2 (P_{NONLIN})}{\partial t^2}$$

The electric field in terms of frequency is given by

$$E = E_0 e^{jw_0 t}$$

Fourier transform of E is given by

$$\tilde{E}(r, w - w_0) = \int_{-\infty}^{\infty} E(r,t) e^{-j(w-w_0)t} dt$$

The wave equation becomes

$$\nabla^2\tilde{E}+\in(w)k_0^2\tilde{E}=0$$

Where $\in(w)=1+\chi^{(1)}(w)+\in_{NL}$

Now the signal equation is given as

$$\tilde{E}(r,w-w_0)=F(\rho,\varphi)\tilde{A}(z,w-w_0)e^{-j\beta_0 z}$$

Where $\tilde{A}(z,w-w_0)$ is envelope function

By substituting in wave equation and separating in two parts

$$\nabla^2F+\{\in(w)k_0^2-\tilde{\beta}^2\}F=0$$

$$-2j\beta_0\frac{\partial\tilde{A}}{\partial z}+(\tilde{\beta}^2-\beta_0^2)\tilde{A}=0$$

Since $\tilde{\beta}$ is very close to β_0, we can write

$$\tilde{\beta}^2-\beta_0^2\approx 2\beta_0(\tilde{\beta}-\beta_0)$$

Using Taylor series expansion, we get

$$\tilde{\beta}(w)=\beta(w)+\Delta\beta(w)$$

And dielectric constant is given as

$$\in=(n+\Delta n)^2$$

Where $\Delta n=n_2|E|^2-j\alpha/2k_0$

Where α is loss term and first term is nonlinearity. Now using the equation

$$A(z,t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{A}(z,w-w_0)e^{j(w-w_0)t}dw$$

Shifting in time domain, we have

$$\frac{\partial A}{\partial z}+\beta_1\frac{\partial A}{\partial t}-j\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2}+\frac{\alpha}{2}A=-j\gamma|A|^2A$$

Which is Nonlinear Schrodinger equation

Where $\beta_2 = -\frac{D\lambda^2}{2\pi c}$ is GVD factor

And $\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$ is Kerr nonlinearity factor

D is dispersion in ps/nm km

ƛ is wavelength in nm

c is speed of light in vacuum

A_{eff} is effective area of core in mm^2

n_2 can be calculated by $n = n_0 + n_2 I$

2.9 Coupled Nonlinear Schrodinger Equation

Nonlinear directional fiber coupler system can be presented mathematically by following pair of coupled nonlinear Schrodinger equations(CNLSE)[7].

$$\frac{\partial A_1}{\partial z} = iK_{12}A_2 + i\gamma(|A_1|^2 + \sigma|A_2|^2)A_1 - \frac{i}{2}\beta_2\frac{\partial^2 A_1}{\partial t^2} - \frac{\alpha}{2}A_1$$

$$\frac{\partial A_2}{\partial z} = iK_{21}A_1 + i\gamma(|A_2|^2 + \sigma|A_1|^2)A_2 - \frac{i}{2}\beta_2\frac{\partial^2 A_2}{\partial t^2} - \frac{\alpha}{2}A_2$$

where A_1 and A_2 are the envelopes in the cores 1 and 2, K_{12} and K_{21} is the coupling coefficient between adjacent guides, $\alpha_{dB} = 4.343\alpha$ is the optical loss in units of dB/m and the parameters γ and b_2 accounts for the effects of SPM and GVD, respectively, in each core of the fiber coupler. The GVD parameter can be positive or negative depending on whether the light pump wavelength (ƛ) is below or above the zero-dispersion wavelength (λ_D) of the fiber.

CHAPTER 3

Literature Review

C.S. Sobrinho et. al. [7] proposed the operating principle of all logical gates and also discussed symmetric NLDC behaviour in pulse position modulation(PPM) the symmetric NLDC includes two important logical operation such as input AND/OR functions. This function is used in TDM for processing signal and transmission characteristics in all optical forms. Symmetric NLDC uses two ultra-short pulses f 2ps and modulated by using PPM technique. The effect of PPM also described. Initially PPM offset increasing when output pulse is at temporal position. The effect of GVD anomalous, SPM and input pulse regime without loss discussed in brief. For NLDC the propagation of signal in core 1 and 2 are discussed. 4 solution of two input AND/OR pulse, output pulse at temporal position, ultra-short pulse modulates by using PPM and variation of coding parameter are also discussed. Without introducing PPM error AND/OR logical operation are easy to examined. To analyse AND/OR logic operation phase control is applied at the input pulse of core 1. In symmetric NLDC the truth table are construct by measuring different offset parameter and phase difference. A stable AND/OR logical operation is obtained by using this truth table.

A. Yariv [8] proposed optical radiation problem including propagation and interaction in dielectric medium and used coupled-mode. In this paper, the problem of energy exchange between two different modes. A general expression of electric to optical modulation, magnetic to electric modulation, filtering of optical signal and photo-elastic is also derived. The problem such as harmonics generate in thin film by using second order of nonlinearities and phase matching of two signals discussed.

S.M Jenson [9] discussed about optical fiber coupler. In this paper also discussed the coherent type nonlinear fiber coupler. This type of coupler used in future for processing the optical signal and it is designed as which work under fast data rate. Due to field overlapping interaction of two coherent signals occurred. Due to this type of overlapping power transfer becomes change and characteristics. Fiber coupler is designed in such a way that includes switches.

G. I. Stegeman et. al. [10] studied the behaviour of signal in third order nonlinearity. The processing of all optical signals is done in directional couplers, Mach-Zehnder interferometers, prism couplers. In this paper the characteristics or properties are discussed experimentally and theoretically. The operating principle of this device is also discussed in brief. In waveguide the device which include the nonlinearities are also discussed.

Stefan trillo et. al. [11] studied the behaviour of short pulses in a directional coupler which was operating in the normal dispersion regime. They used birefringent rocked fiber filter. The two polarized mode which are orthogonal is coupled. They showed that significant power dependent switching occurs between polarization modes only if input pulse width is longer than fundamental lower width. They found that when input pulse gets narrower temporal broadening increases the effective switching power of NLDC.

J. M. Fang et. al. [12] proposed photonic absorption for NLDC and also discussed switching characteristics. They considered large nonlinear index of refraction. A certain quantity of two photon absorption (TPA) was discussed. TPA is important term in optical that limit optical switching. They proved that switching is possible in case of two-photon absorption. It has been concluded that the input pulse and output pulse help in maintaining the shape of pulse.

Y Zhu et. al. [13] analysed numerical simulation of a passive twin-core fiber coupler ring laser based on nonlinear optical switching. They considered effects of Raman self-frequency-shift, which must be included for ultrashort pulses, and gain saturation which also must be included for lasers with MHz repetition frequency .The laser is analysed by comprehensive coupled nonlinear Schrodinger equations. For a given beat-length of the twin-core fiber and a given amplifier saturation power they determined conditions for stable pulsed operation of the passive fiber ring laser. They found non-soliton and chirped pulse regimes in addition to the soliton mode locking regime. They have shown that by proper balance between gain saturation, nonlinear switching, self-frequency shift, bandpass filtering and output coupling pedestal-suppression-ratios of better than 40 dB and durations of less than 0.5 ps can be generated.

Tetsuro Yabu et. al. [14] proposed a new element consisting of a two-mode nonlinear waveguide made of Kerr-like material for all-optical logic circuits. The proposed element, installed into the Mach–Zehnder interferometer, behaves like a phase shifter. Although the optical waves propagating in the proposed element were of single wavelength and identical in oscillating with more than one orientation, its operation was insensitive to the relative phase difference between the incident signals. Using this element, various logic functions such as inverters, distributors, and AND gates could be realized.

M. Liu et. al. [15] investigated the effects of intermodal dispersion. Behaviour in a passive coupler which have two core fiber coupler was also discussed. The effect of intermodal dispersion is also studied in active or passive fiber coupler. In active coupler behaviour of intermodal dispersion is investigated. In passive the presence of intermodal dispersion create some problems such as pulse distorted and break of pulses. The overlapping of intermodal dispersion and gain of the bandwidth was observed. The break of pulse controlled or removed by using the limited bandwidth which has variable gain.

W.B. Fraga et. al. [16] investigated the switching characteristics of three different type of asymmetric NLDC. The positive and negative characteristic of self-phase modulation profile (SPM) also mentioned in this paper. The one of the channel linked in SPM profile is asymmetric. The asymmetry was attached to the profile of the SPM of one of the channels. The signal transmission properties of the switching device and transmitted a signal via the direct-channel link and cross-channel link. This paper proposed a work of the extinction ratio (Xratio) was done. The operating principle of direction coupler was discussed, the behaviour of AND, XOR and OR gates are discussed in the NLDC i.e. nonlinear profile. Entire NLDCs, an AND port with induced variable gain was observed. In directional coupler as a logic gate, the nonlinear profile has to be controlled in order to better the transmission factor through the extinction ratio (Xratio).

M. G. da Silva et. al. [17] reported a general expression of ultrashort soliton in NLDC and periodically modulated dispersion are derived, a numerical solution of ultrashort optical soliton and comparison of NLDC and soliton pulse has been discussed. The simulations took into effect of different amplitude and phase modulations. Using the technique introduced by Anderson, the coupled nonlinear Schrödinger equations (NLSEs) were converted into a variational problem with Lagrangian equations of motion with a finite number of freedom i.e. m and obtain the transmission characteristics of the device. The transmission factor, extinction ratio (Xratio), the critical energy, and the crosstalk (Xtalk) for solitons were studied for varying input pump powers. The analytical and numerical comparison was made. On comparison of both the techniques, in the PMDF coupler of soliton give good behaviour of the switching for input pump energies i.e. less than the critical energy of the NLDC.

A.M Bastos et. al. [18] proposed an all-optical logic gate based on nonlinear slot-waveguide couplers. NOT, OR, and AND logic gates could be realized by using a single optical nonlinear directional coupler. Polarization dependencies of these waveguides were effectively utilized for realization of polarization-independent optical NLDC in the linear region and polarization-dependent all-optical switches in the nonlinear region. All the simulations were done for three-dimensional nonlinear waveguide structures by using numerical methods based on the full-vector finite-element method especially developed for nonlinear waveguides.

Xiujun He et. al. [19] studied the switching characteristics of asymmetric two core i.e. core 1 and 2 nonlinear fiber. This paper concludes that by using opposite sign switching efficiency is higher than using same sign of dispersion values. If efficiency of one core in fiber coupler is decreased the efficiency of same sign of dispersion values is higher. Meanwhile if the coefficient of two fiber was opposite than with same sign threshold power of one switch is lower than other. The paper concludes that asymmetric NLDC have high switching characteristics and low switching threshold power in comparison to Symmetric NLDC.

Prasanta Mandal et. al. [20] proposed a new method to construct all optical logic operation like OR and NAND based on nonlinear directional coupler. The optical switching could be achieved by Mach-Zehnder interferometer modulator. Effective switching was done by modifying the coupling length between the coupler waveguides with the help of an optical signal. As all-optical switching was used, a very high data rate could be achieved. Since NAND gate is a universal logic gate, any other logic gate can be realized using NAND gate.

Xiujun He et. al. [21] studied the switching characteristics and output coupling ratio of nonlinear directional fiber couplers (NLDC). In this paper input power and width of the input signal are discussed. Optical coefficient of soliton pulse is also discussed. The switching efficiency was improved by varying ratio of input and output power of core 1. Different output input matching ratio was obtained by varying gain of input cores 1 and 2. The gain could be changed by varying pump power of the optical amplifiers. Thus, variable fiber coupler with changeable output coupling could be made.

Xiujun He [22] analysed a numerical study of phase-induced switching in NLDC and the maximum output coupling ratio by the relative phase change of a control signal was carried out for appropriate input powers, large coupled coefficient and small input soliton width. It was shown that coupling coefficient, input powers ratio and input soliton width play significant roles in soliton switching and these effects might lead to soliton switching if the phase shift of the control signal was monitored accordingly. The switching characteristics were improved by phase induction and different output coupling of NLDC was obtained. Thus, variable fiber coupler with changeable output coupling could be made.

Gang Wang et. al. [23] proposed all-optical AND/XOR gates for non-return-to-zero (NRZ). In this paper expression of semiconductor optical amplifier used with Mach–Zehnder interferometers (SOA-MZIs) has been derived. The complementary data with the processed data was used to modulate the SOAs which could be used to reduce the patterning effects by accelerating rising and falling edges and increase the data rate to 40 Gbps. In the proposed AND gate, the SOAs were differentially biased to balance the phase in data bit ‘0’. The high output signal is obtained is superior for both AND/XOR gates and quality factor obtain is order of ($Q > 6$).

Yusheng Bian et. al. [24] theoretically realized all fundamental optical logic gates by using a multi-channel arrangement of functional units based on one-dimensional (1D) metal–insulator–metal (MIM) structures. The working principle and necessary conditions for different logic functions were analysed and explained numerically by means of the finite element method. In contrast to most of the previous experiments that require multiple configurations to achieve different logic functions, a single configuration could realize all fundamental functions. It was shown that by giving optical signals to different input channels, the device could uses the logic gates such as OR, AND and XOR. By inputting signal in the control channel, more logic gates including NOT, XNOR, NAND and NOR could be realized. For these logic gates, between Boolean logic states "1" and "0" the intensity of high contrast ratio could be achieved at the telecommunication wavelength. The new all-optical logic device is simple, small in size and efficient. The proposed method could be applied to many nano-photonic logic devices, thus design is very useful for further development in on-chip optical computing.

Mehdi Tajaldini et. al. [25] proposed modal propagation analysis (MPA) as an important approach. In this paper work was done on multimode interference on small dimension. The finite-difference method was used as a numerical method for solving the nonlinear modal equations and calculating the modal propagation constant. The characteristics of two initial modes show the changes that are introduced by nonlinear effects, in the direction of propagation the transformation of a sinusoidal profile changes to a Gaussian pulse, the increased oscillation of the induced phase, and variable wavelength shifting. Further, all these changes work differently for each mode. The Gaussian pulse combined with other observed phenomenon gives more efficient interferences among the modes and it show switching applications at a small Multimode interference. The steps for designing an optimum switch needs the implementation of a series of various evaluations of the switching operation based on linked parameters, such as the contrast ratio between the ON and OFF outputs, known as the performance gain of switch (SPG); this parameter was used to make the best switch through the width, and the power loss was used in the same way. The results indicated the multimode interference length scheme efficiency which is of approximate $10\mu m$ and that SPG depends on both output width and input intensity.

A. Govindaraji [26] reported a numerical study of propagation of pulse and nonlinear directional coupler switching with the consideration of self-steepening effects and third order dispersion. The Split Step Fourier Method (SSFM) was used to plot the switching characteristics of nonlinear directional couplers by varying the third order dispersion and self-steepening values. The transmission factor was improved for lower values of third order dispersion at low input power but was deteriorated at high input power. It was observed that the energy transfer from one core to another is not occurred due to change in the shape of the input pulse.in super Gaussian due to change in pulse energy transfer occurred. The combined effect of TOD and SS further decreased the switching characteristics.

Qiliang Li et. al. [27] studied the behaviour of nonlinear directional coupler on all-optical logical gate in the presence of cross-phase modulation. OR gate, XOR gate and a new logical function based on nonlinear directional coupler, which can be used in transmission of signals in all-optical systems, were examined. Initially, the switching effect on pump power was evaluated. A pulse was imported into the nonlinear directional coupler and simultaneously a pump light was added using wavelength division multiplex in order to make use of Kerr effect and obtain XPM (cross phase modulation). The scenarios for the logical gate were analysed, and a switching characteristic curve was drawn via Matlab. Finally, the truth table was defined and it was clear that OR gate, XOR gate and a new logical function could be realized by changing the pump power. The study also indicated that by varying the input pulse’s phase, switching could be realized. The truth table was again defined and it could be observed that different logic gates were realized.

J. S. de Almeida et. al. [28] presented a numerical expression of the transmission and switching of fundamental solitons in asymmetric NLDC. This asymmetric NLDC uses dispersion decreasing fibers (DDF) that reduce the dispersion of the fiber. Two type of parallel fiber has been discussed here one which has reduced dispersion profile and another is constant profile. The extinction ratio are derived in this paper and concluded that it is 1.66 db for AND/OR logic gates. The truth table for AND/OR are also derived. Six different profiles of dispersion decreasing fibers (DDF): constant, exponential, Gaussian, hyperbolic, linear, and logarithmic were investigated.

Amir Mostofi et. al. [29] proposed coupling effect. Also describe the effect of coupling varied by using both dynamic and static in asymmetric NLDC with soliton switches. The effect is too strong near the switching region by using continuous wave. With the length of coupler effect kept increasing fast as double rate for linear coupling at odd multiple length i.e. $\pi/2$, in the case dynamic NLDC. In static soliton switching the effect is varied linearly that is bistability phenomenon occurs. At first bifurcation point, the effect is maximum. With no distortion of pulse or no emission of dispersive medium the soliton pulse is stable.

Nail Akhmediev et. al. [30] proposed two new families of coupled soliton in NLDC. The soliton pulse of new state with bistablity diagram has been discussed in this paper. In symmetric NLDC waveguide the bi-stability diagram for fiber coupler is same as for stationary wave. Physical reason behind this phenomenon has been discussed.

Zhongxi Zhang et. al. [31] describe a fourth-order Runga-Kutta. In order to solve the coupled NLDC Runga-kutta technique was applied. The birefringence of CNLSE is varied when light is propagated in the fiber. RK4IP includes error of computation by using CNLSE. RK4IP computation error is less in case of split step approximation. The step size of RK4IP could have the same magnitude as the dispersion length and the nonlinear length of the directional fiber, given the birefringence effect was less. For communication fiber couplers with random birefringence, the step size of RK4IP could be greater than the correlation length and the length that is above the correlation of the couplers, depending on the relation between linear and nonlinear effects. The general expression of local birefringence is also derived and the effect of kerr nonlinearities is considered. The RK4IP results conformed to those obtained from Manakov-PMD approximation.

M.S. Ismail [32] presented that the coupled nonlinear Schrodinger equation could model equation for optical fiber with linear birefringence. A finite element scheme was derived to solve this equation, this method was tested for stability and accuracy, and many numerical tests have been conducted. The scheme was of second order in both time and space dimensions and was highly stable. The scheme was quite accurate and efficient and described the interaction picture clearly. The derived method could be easily generalized to solve N coupled nonlinear Schrodinger equation.

Shenggao Zhou et. al. [33] considered the numerical simulation of coupled nonlinear Schrödinger equations on unbounded domains. This paper describes the splitting technique that realizes linear and nonlinear problem in few seconds of time. Linear problem uses two NLDC on Unbounded domain to disable unbounded domain into finite some temporary boundaries defined. In coupled NLDC Ordinary differential equation method was applied. To measure, our method is effective. Perfectly matched layer technique is applied which calculate cost and accuracy of system.

I. M. Uzunov et. al. [34] presented an analysis including all the aspects of the propagation of short pulses in nonlinear directional couplers. The pros and cons of the variational approach to evaluate power-controlled and phase-controlled pulse switching were discussed. Depending on calculation of beam propagation, an expression that accounts for variable phase, width, amplitude and chirp of the pulses was proposed. The derivation of Euler-Lagrangian equations for the pulse parameters was done and their solutions were found out. A good conformation of the switching curve related to power-controlled switching with beam propagation results was found. Various pulse parameters were described adequately by the model used. Further, necessary criteria for efficient phase-controlled switching might be easily derived by using the model.

Mohammed Z Ali et. al. [35] suggested the use of soliton in fiber is very effective because it does not distort the signal and does not limit on number of repeaters and optical amplifier. The response of signal in Gaussian and soliton pulse was discussed and draw. Three segment of cable is used in this paper. The different parameter such as phase matching, pulse broadening ratio, the ratio of output and input power and amplifier used were discussed in this paper. This paper concludes that performance of Soliton pulse is more superior than Gaussian pulse because soliton pulse does not change their shape with change in refractive index.

Amarendra K. Sarma [36] reported dark soliton switching in a NLDC in the presence of third-order dispersion, intermodal dispersion, Raman Effect, cross-phase modulation (CPM) and self-steepening effect. It was shown that except CPM all other perturbative effects had no effect on the transmission factor of the dark soliton switch, which was an advantage over the bright soliton switch. Although CPM led to an increase in the critical power of dark soliton switching, the soliton propagated constantly inside the coupler.

Sotiris Droulias et. al. [37] studied in the presence of intermodal dispersion (IMD) the behaviour of NLDC. The mathematical model of coupled nonlinear Schrodinger equations (CNLSE) was described. The behaviour of normal-mode theory was discussed. The propagation behaviour of soliton pulse was also discussed in brief. The optical pulse is given to one of the two input port for light-wave system. The effect of intermodal dispersion on NLDC has been mentioned. The intermodal dispersion affect the solitary use that is it distorts the unity pulse.

Qiliang Li et. al. [38] proposed switching characterstic of NLDC in presence of split step transforms. The results in case of Variational Approach gives 2nd order coupling coefficient and chirp length decreased by using chirp. Without using this chirp threshold power is increased which is an important switching property. It showed that the second-order coupling coefficient and chirp reduce the coupling length, and the second-order coupling coefficient makes the switching characteristics become clearer and threshold power is increased without having chirp. The results in case of SSFT obtain IMD distort the signal and coupling effect the chirp length and threshold power.

Thiab R. Taha et. al. [39] described the nonlinear Schrodinger equations theory, applications and its limitation. In this paper different regimes are discussed in brief. The general expression for Parallel SSF methods is discussed. These methods were implemented on the Origin 2000 multiprocessor computer. The numerical experiments showed that these methods gave accurate results and considerable speedup.

P. M. Ramos et. al. [40] showed that soliton do not break up in coupling process and are very suitable for all optical processing. They introduced a new variational approach for the cross phase modulation effect on self-routing pulse switching in optical fibers. They found out that their analytical results and numerical results by split step fourier method have matched exactly.

Youfa Wang et. al. [41] studied transmission of optical signal through nonlinear directional couplers cascaded and they theoretically proved the logic operations including AND, OR, XOR, NOR, NXOR, and NAND can be implemented in the same cascaded nonlinear fiber coupler structure using tailoring function. It is realized that output level of device can be adjusted by varying coupling coefficient.

CHAPTER 4

All-optical Logic Gates in an Asymmetric Nonlinear Directional Coupler

4.1 Introduction

Nonlinear directional couplers (NLDCs), passive devices, have attracted considerable attention because of their many applications in optical systems. Numerical analysis of nonlinear directional fibre coupler with periodically modulated dispersion was investigated. Gain induced soliton switching and phase induced soliton switching was also investigated. One of main attractive feature is switching at high bit rates in an all optical systems. The use of nonlinearities in optical fiber as switching purpose has been investigated extensively. Three or more core couplers have also been investigated in order to get desired sharp switching dynamics.

4.2 Analysis and Methodology

Let us consider a directional coupler at a small power level; in port A, a pulse with small power and a pump signal with large power are coupled into port A by wavelength division multiplex (WDM), as shown in figure 9, and the pump signal is permanently reserved in channel 1 for the reason that the wavelength of the pump signal is dissimilar from that of the input signals[27]. The input pump signal creates cross-phase modulation relative to the pulse in the channel owing to the Kerr effect, such that the symmetry coupler is converted to an asymmetric coupler. At the small power level, the coupler acts as a linear device. By progressively incrementing the power of pump signal, the pump power touches threshold power, and the splitting ratio becomes close to 1:1 due to temporary coupling and cross-phase modulation. The cross-phase modulation will stop the signal pulses from swapping between two cores in the coupler if the pump power is large than the threshold power.

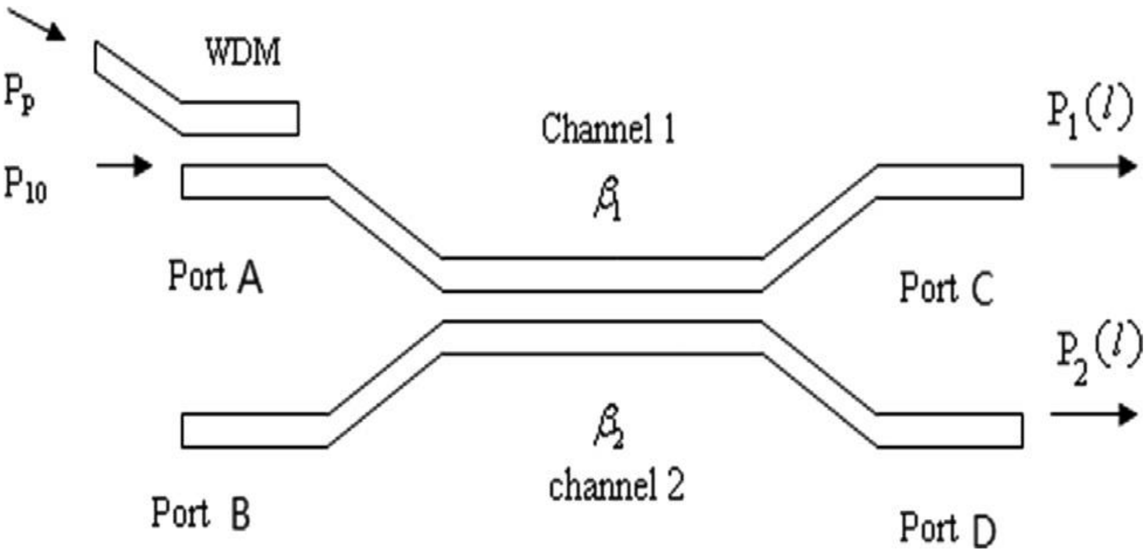

Figure 4.1 Non-linear directional coupler[27]

First of all, according to the coupled nonlinear Schrödinger equations, we ignore the time-related items and have the following set of equations [3]:

$$\frac{dA_1}{dz} = iK_{12}A_2 + i\beta_1 A_1 + 2i\gamma P_P A_1 \quad (1)$$

$$\frac{dA_2}{dz} = iK_{21}A_1 + i\beta_2 A_2 \quad (2)$$

Where β_1 and β_2 are the propagation constants of core 1 and core 2, respectively, K_{12} and K_{21} are the coupling parameters, γ is the nonlinearity parameter, and Pp is the pump light.

Furthermore, we make transformation as follows: $A_1 = P_1 e^{i(\beta_1+\beta_2/2)z}$ and $A_2 = P_2 e^{i(\beta_1+\beta_2/2)z}$; therefore we can obtain the following equations:

$$\frac{dP_1}{dz} = iKP_2 + i\varepsilon_1 P_1 \quad (3)$$

$$\frac{dP_2}{dz} = iKP_1 + i\varepsilon_2 P_2 \quad (4)$$

In the equations, we make the coupling parameters $K_{12} = K_{21} = K$, $\Delta\beta = (\beta_1 - \beta_2/2)$, $\varepsilon_1 = \Delta\beta + 2\ \gamma\ Pp$ and $\varepsilon_2 = -\Delta\beta$.

Then, solving Eqs. (3) and (4), we can assume the initial conditions $P_1(0) = P_{10}$ and $P_2(0) = P_{20}$ and get the following results:

$$P_1(z) = e^{ik_1 z}[P_{10}\cos(k_2 z) + i(\frac{k_1}{k_2}P_{10} + \frac{K}{k_2}P_{20})\sin(k_2 z)] \quad (5)$$

$$P_2(z) = e^{ik_1 z}[P_{20}\cos(k_2 z) - i(\frac{k_1}{k_2}P_{20} - \frac{K}{k_2}P_{10})\sin(k_2 z)] \quad (6)$$

Where $k_1 = \gamma\ Pp$ and $k_2 = \sqrt{(\gamma\ Pp\ )^2 + K^2}$, and when solving the equations, we made an estimate as $\Delta\beta = 0$.

Lastly, we use the extinction ratio to judge the switch. The extinction ratio of a switch is defined as the ratio of the on state output power to the off state output power. It must be as large as possible. To calculate the extinction ratio, we use the following equation[16]

$$X_{ij} = \frac{\int_{-\infty}^{\infty}|P_i|^2 d\tau}{\int_{-\infty}^{\infty}|P_j|^2 d\tau} \quad \text{(i,j=1,2)} \quad (7)$$

Where τ is time.

If the extinction ratio uses dB as a unit, (7) becomes:

Extinction _ ratio[dB]= $Xratio_{ij} = X_{ij}(dB) = 10log_{10}X_{ij}$ (8)

We describe the transmission which is used to define the switching performance:

$$T_i = \frac{\int_{-\infty}^{\infty}|P_i|^2 d\tau}{\int_{-\infty}^{\infty}|P_{10}|^2 d\tau} \quad \text{(i=1,2)} \quad (9)$$

We discover another situation in which the input channels are excited by a phase difference between two pulses. A dephasing value ($\Delta\emptyset$) is added into the initial input P_{10}, so (5) and (6) become as follows:

$$P_1(z) = e^{ik_1 z}[P_{10}\, e^{i\Delta\emptyset}\cos(k_2 z) + i(\frac{k_1}{k_2}P_{10}e^{i\Delta\emptyset} + \frac{K}{k_2}P_{20})\sin(k_2 z)] \quad (10)$$

$$P_2(z) = e^{ik_1 z}[P_{20}\cos(k_2 z) - i(\frac{k_1}{k_2}P_{20} - \frac{K}{k_2}P_{10}e^{i\Delta\emptyset})\sin(k_2 z)] \quad (11)$$

We study a situation where we introduce gain of core 1 and 2. So (5) and (6) becomes as follows:

$$P_1(z) = e^{ik_1 z}[P_{10}g_1\cos(k_2 z) + i(\frac{k_1}{k_2}P_{10}g_1 + \frac{K}{k_2}P_{20}g_2)\sin(k_2 z)] \quad (12)$$

$$P_2(z) = e^{ik_1 z}[P_{20}g_2\cos(k_2 z) - i(\frac{k_1}{k_2}P_{20}g_2 - \frac{K}{k_2}P_{10}g_1)\sin(k_2 z)] \quad (13)$$

4.3 Results and Discussion

Switching Characteristics

The following parameters are taken in our study:

Coupling coefficient, K = 0.05 cm^{-1}

Nonlinear coefficient, γ = 1.5 × 10^{-4} /W cm

Coupling length, L_C = π/2κ = 31.4 cm

Pump power = 0 to 1000 kW

Wavelength of pump = 850 nm

Wavelength of signal = 1550 nm

The initial pulses at the input port are given by P_{10} = 1 mW, P_{20} = 0 and P_{10} = 1 mW, and P_{20} = 1 mW, respectively. The threshold power (P_{pth}) is about 70.9 kW. Next the pump power is normalized by the threshold P_{pth}, namely, $p_p = Pp/P_{pth}$.

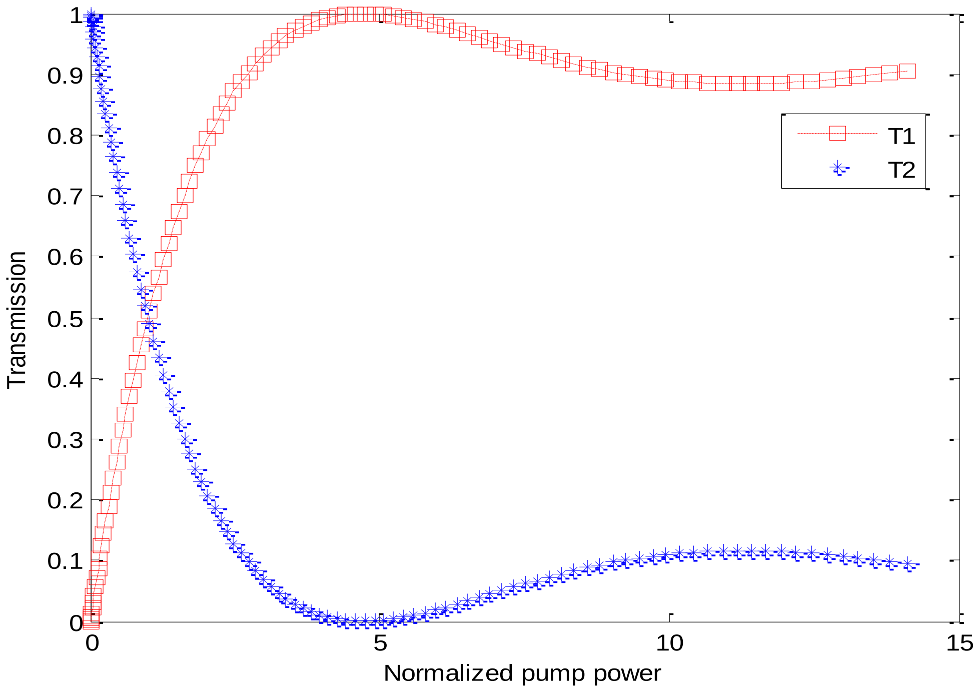

Figure 4.2 The transmission factor as a function of the pump power with an input pulse in port A

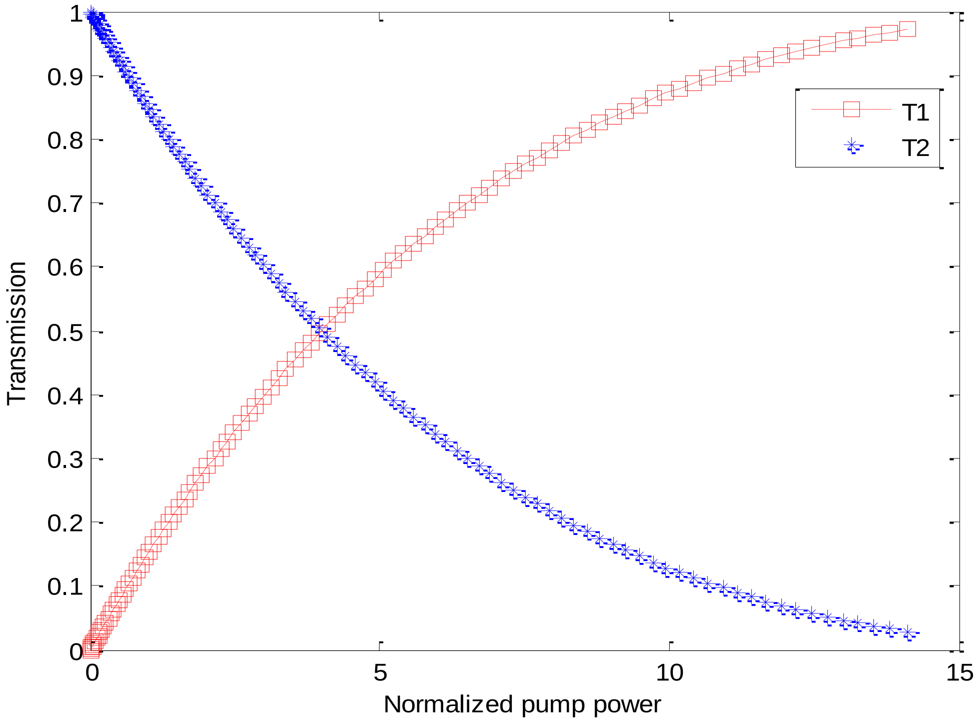

Figure 4.3 The transmission factor as a function of the pump power with an input pulse in port A and K = 0.1

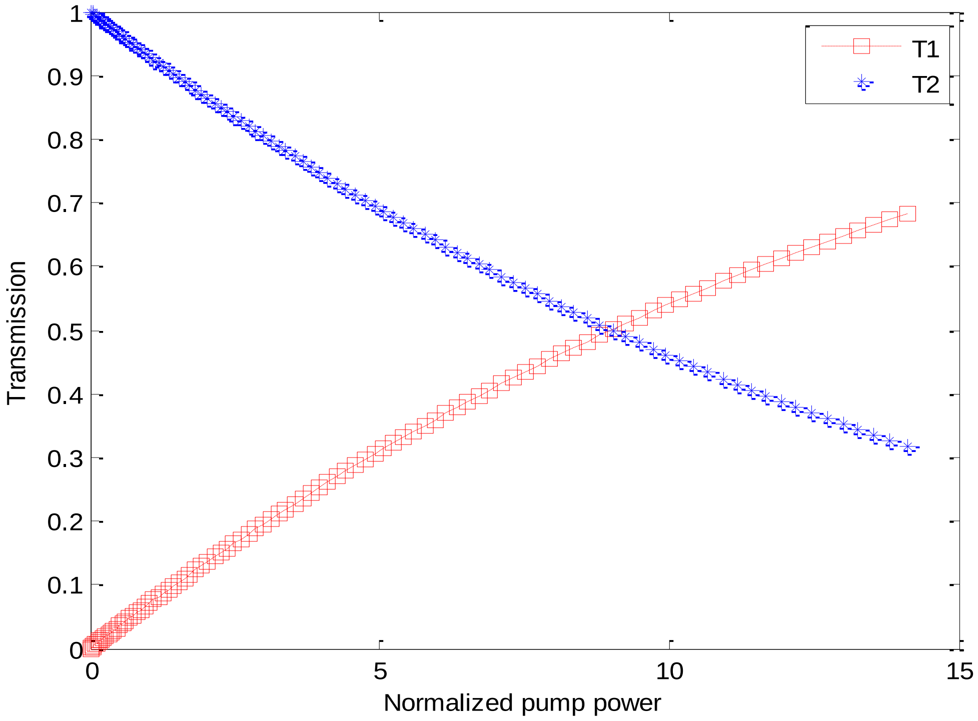

Figure 4.4 The transmission factor as a function of the pump power with an input pulse in port A and K = 0.15

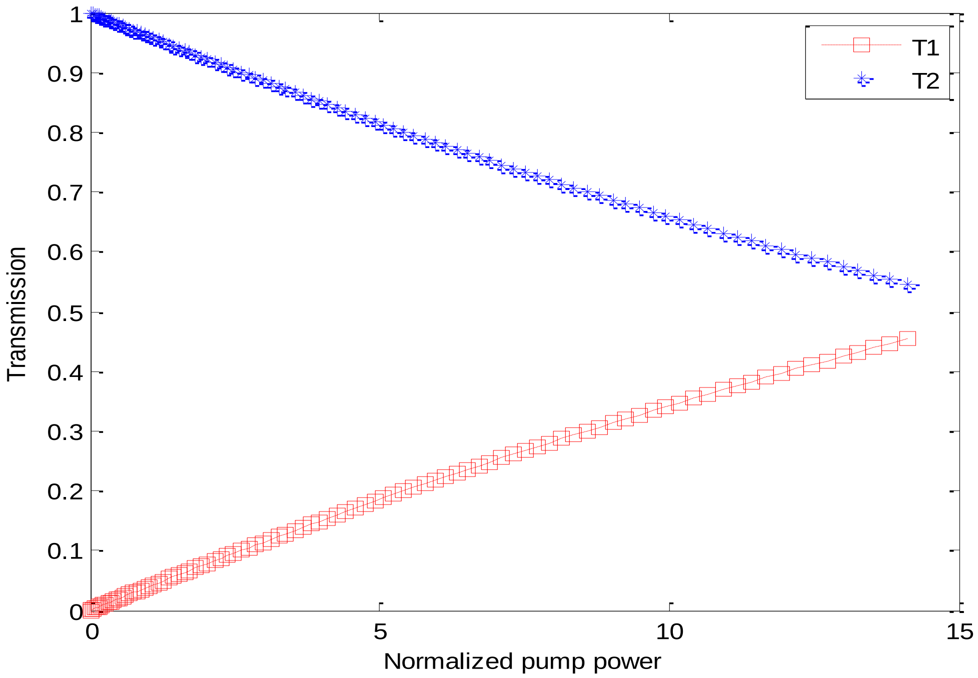

Figure 4.5 The transmission factor as a function of the pump power with an input pulse in port A and K = 0.2

From figures 10-13, we observe that the transmission coefficient for core 1 has a maximum value of 1 for K = 0.05 and the transmission coefficient for core 2 has a minimum value of 0. For K = 0.1, the values are 0.97 and 0.02 respectively. For K = 0.15, the values are 0.68 and 0.31 respectively. For K = 0.2, the values are 0.45 and 0.54 respectively. We conclude that by increasing the value of K, the maximum value of transmission coefficient for core 1 decreases and the minimum value of transmission coefficient for core 2 increases.

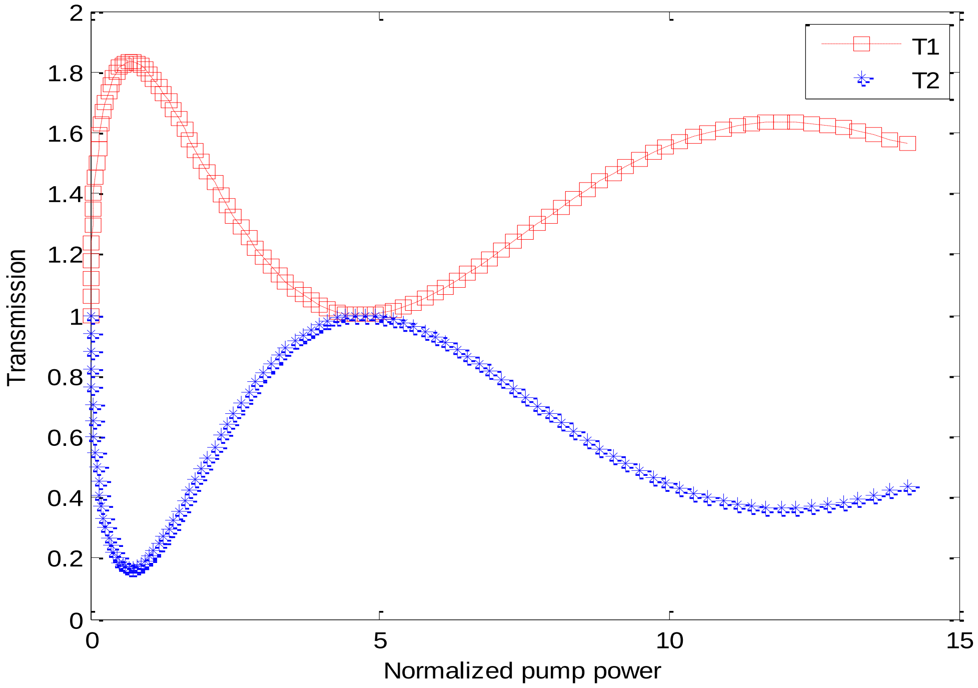

Figure 4.6 The transmission factor as a function of the pump power with an input pulse in ports A and B for K = 0.05

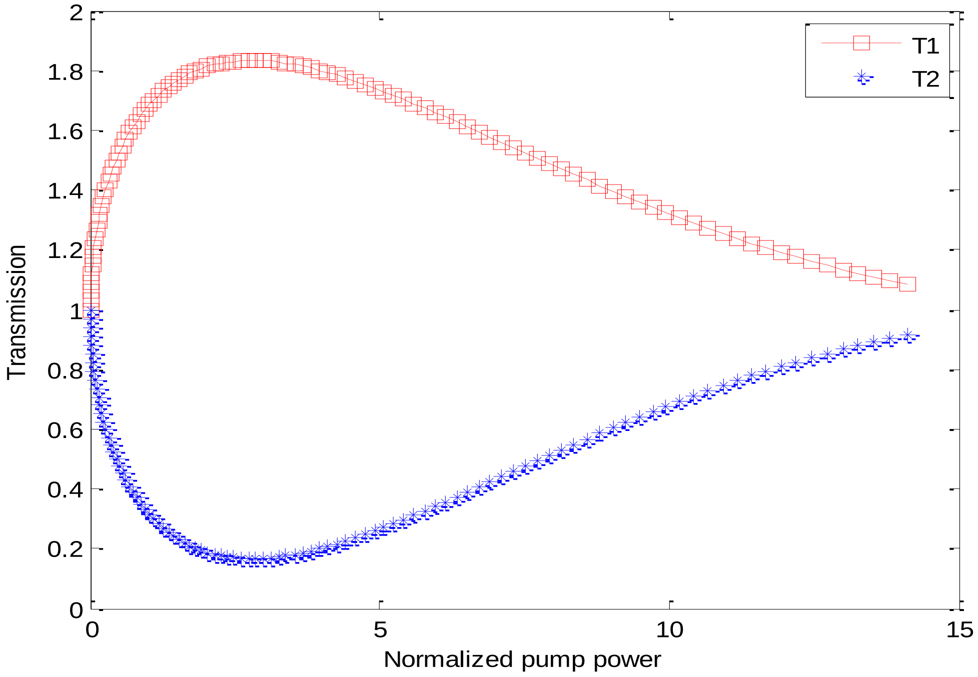

Figure 4.7 The transmission factor as a function of the pump power with an input pulse in ports A and B for K = 0.1

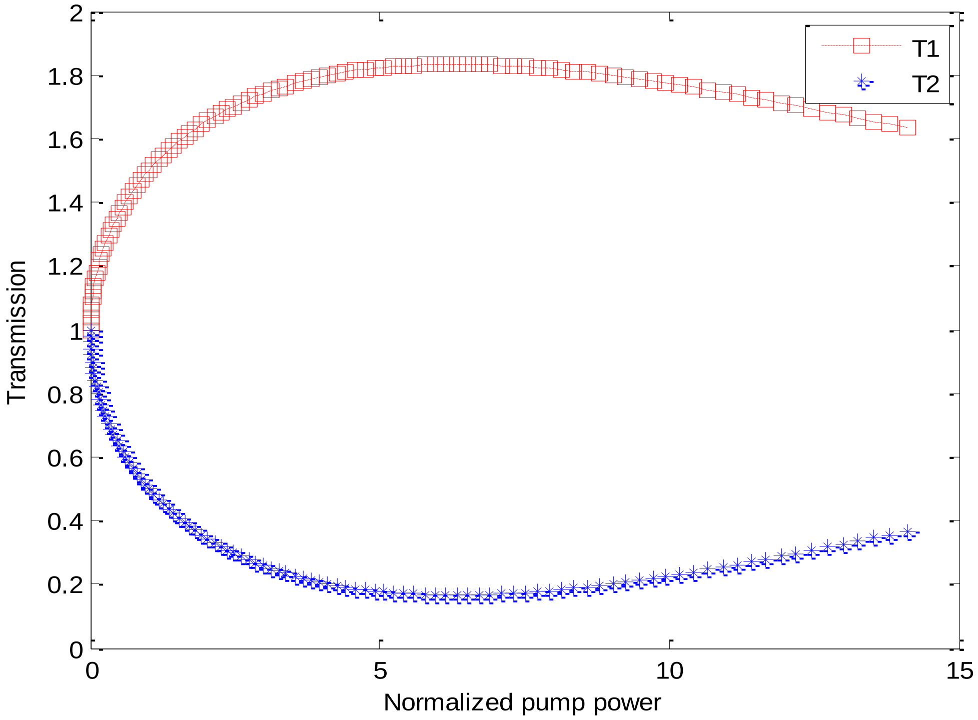

Figure 4.8 The transmission factor as a function of the pump power with an input pulse in ports A and B for K = 0.15

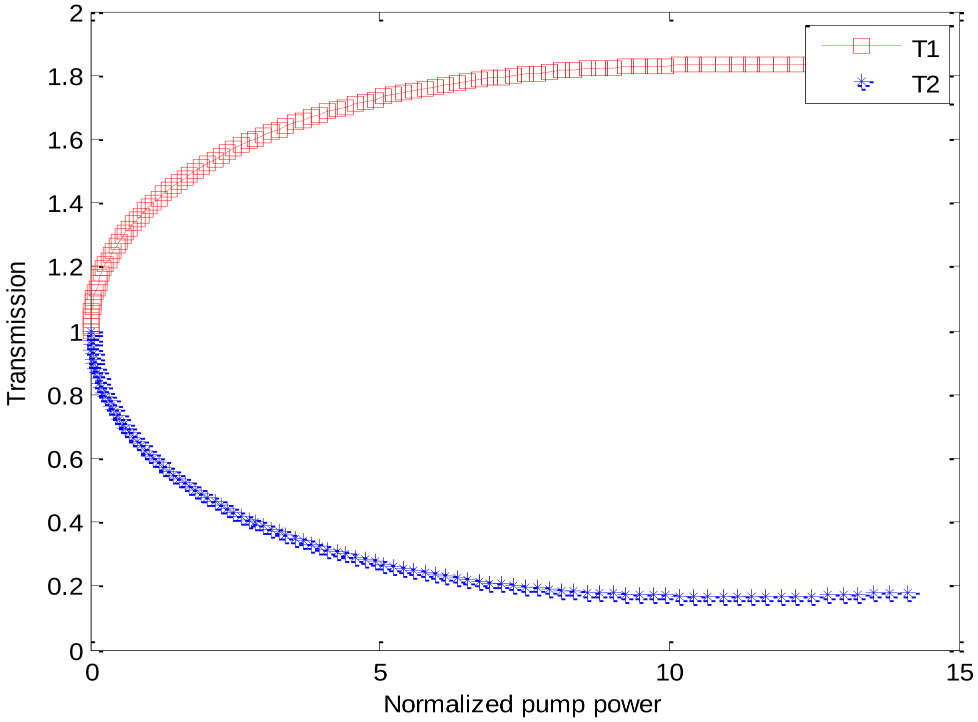

Figure 4.9 The transmission factor as a function of the pump power with an input pulse in ports A and B for K = 0.2

From figures 14-17, we observe that the peak value of transmission coefficient is obtained for an input power of 0.74 for K = 0.05. For K = 0.1, the value is obtained at an input power of 2.85. For K = 0.15, the value is obtained at an input power of 5.77. For K = 0.2, the value is obtained at an input power of 10.19. We conclude that by increasing the value of K, the input power for peak value of transmission coefficient also increases.

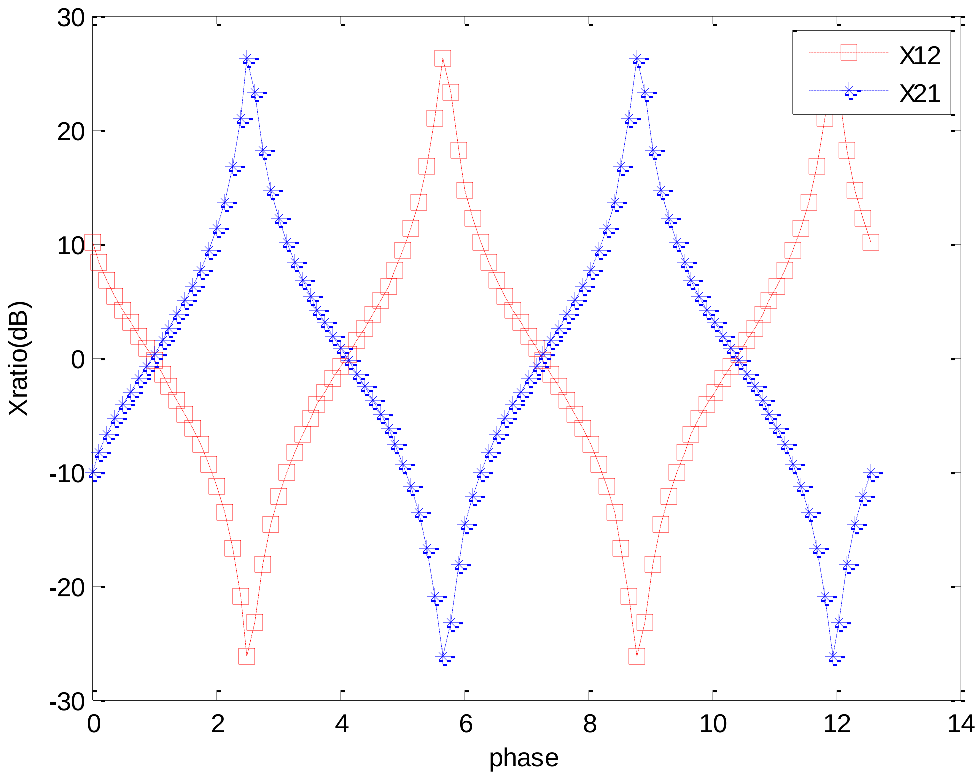

Figure 4.10 The Xratio in dB as a function of phase when p_p= 0.88 and P_{10}=P_{20}= 1 mW and K= 0.05

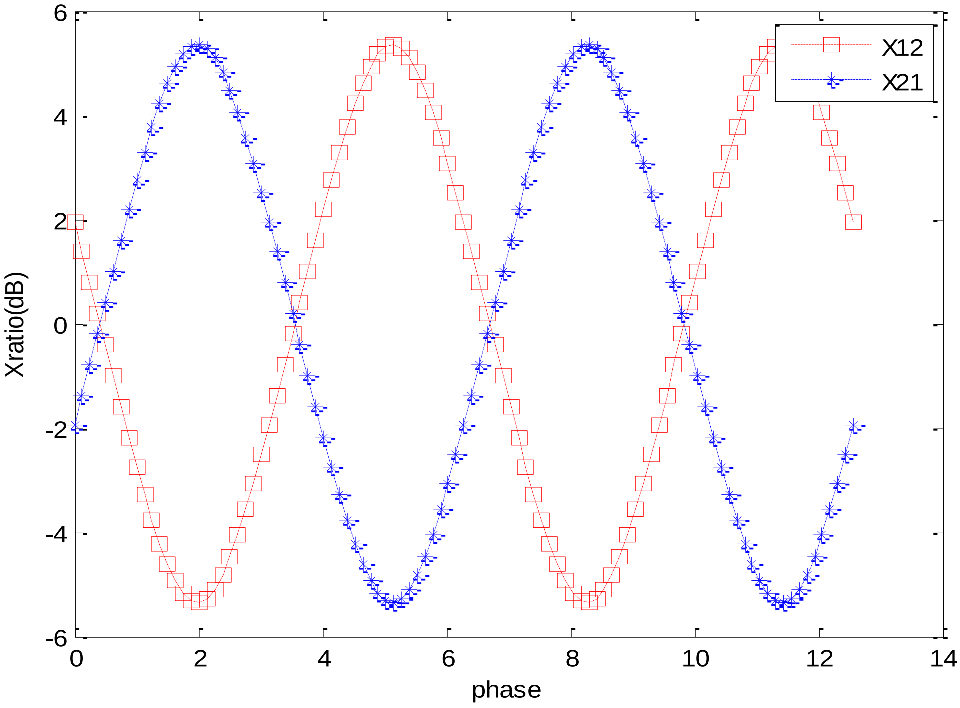

Figure 4.11 The Xratio in dB as a function of phase when p_p= 2.86 and P_{10}=P_{20}= 1 mW and K= 0.05

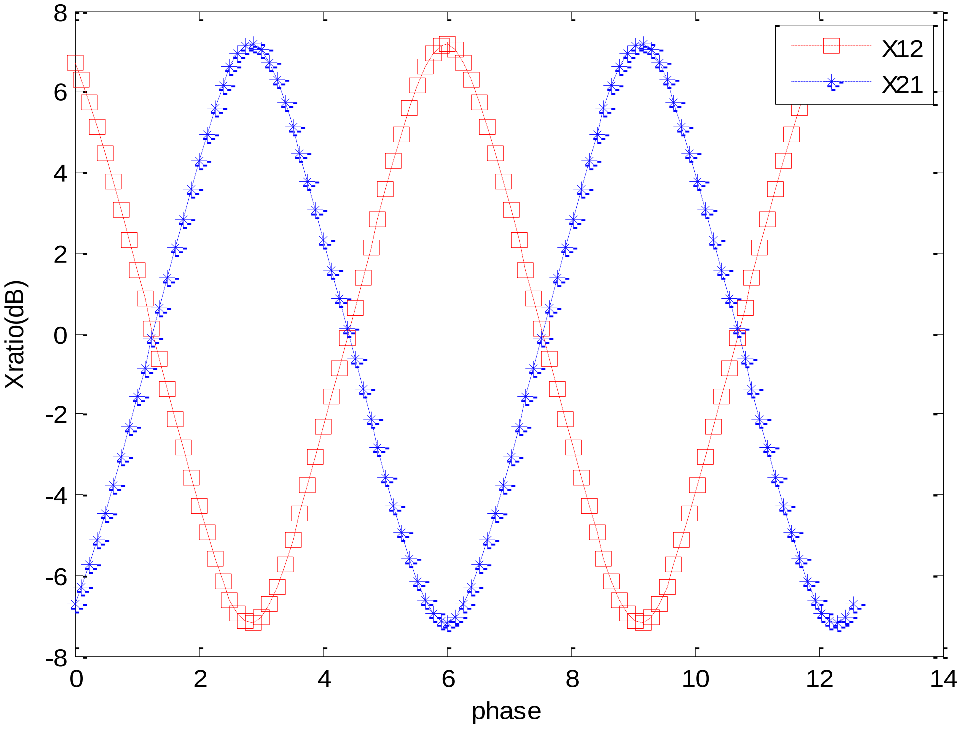

Figure 4.12 The Xratio in dB as a function of phase when p_p= 0.88 and P_{10}=P_{20}= 1 mW and K= 0.1

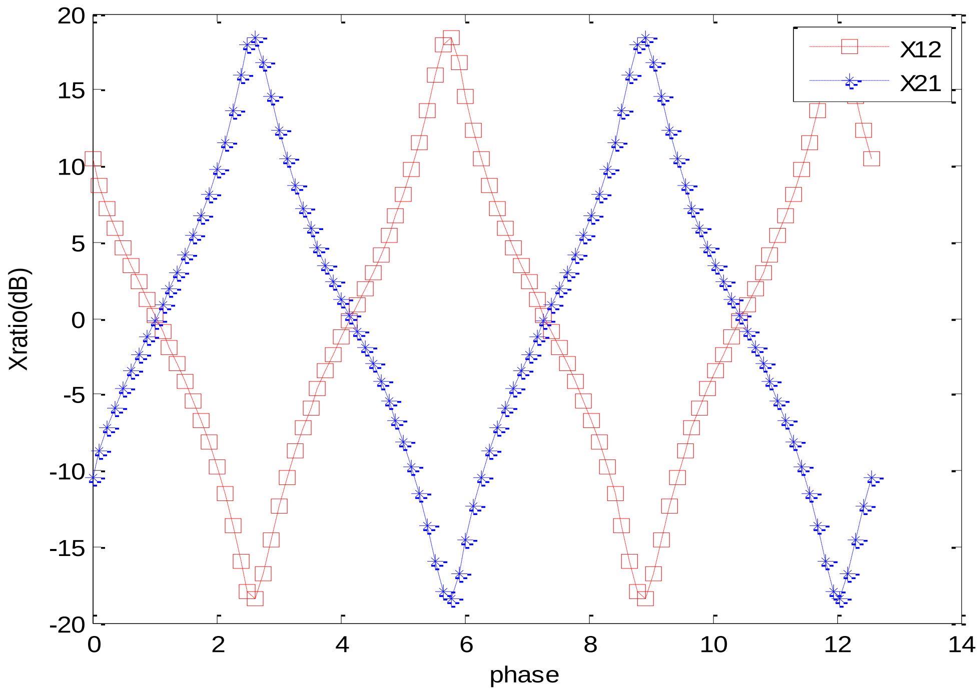

Figure 4.13 The Xratio in dB as a function of phase when p_p= 2.86 and P_{10}=P_{20}= 1 mW and K= 0.1

Next we consider two situations when p_p< 1 and p_p> 1. Figs. 20-23 show the Xratio level as a function of dephasing value Δϕ, when p_p= 0.88 and p_p= 2.86, respectively with varying coupling coefficient. We notice that by increasing the value of coupling coefficient from 0.05 to 0.1 the graphs for pump power p_p< 1 and p_p> 1 are reversed.

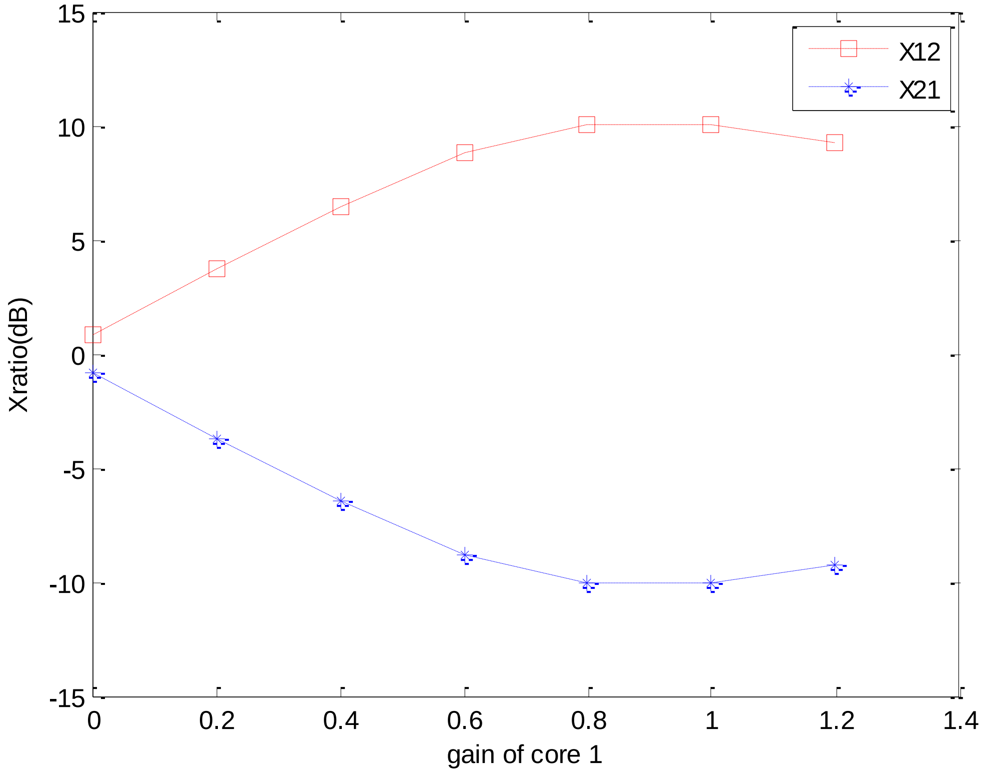

Figure 4.14 The Xratio level as a function of gain at core 1 when p_p= 0.88 and $P_{10} = P_{20} = 1$ mW

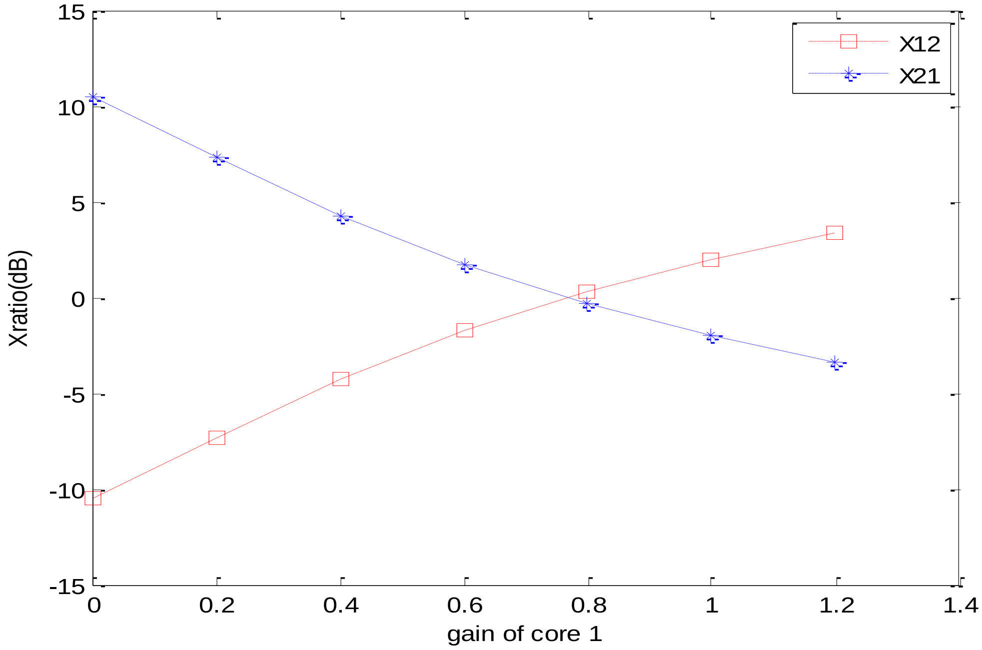

Figure 4.15 The Xratio level as a function of gain at core 1 when p_p= 2.86 and $P_{10} = P_{20} = 1$ mW

Now we study the effect of different values of gain of core 1 on the extinction ratio. We discuss two situations when p_p< 1 and p_p> 1 for analysing extinction ratio when p_p= 0.88 and p_p= 2.86. From fig. 3, we observe that X_{12} has maximum value of 10.18 dB for gain of 0.9 and X_{21} has minimum value of -10.18 dB for gain of 0.9. From fig. 4, we observe that X_{12} has maximum value of 3.356 dB for gain of 1.2 and X_{21} has minimum value of -3.356 dB for gain of 1.2.

Next we study the influence of different gain on the Boolean operation of coupler. The gain values (g = 0.2 and g = 1.2) have been selected in a way to provide the best average values of Xratio for the configurations (0,1), (1,0) and (1,1), so it is easy to judge the logic gates. From tables 1 and 2, it can be seen that an OR gate, a XOR gate and a new logic expression D = $\bar{A}.B$ has been realized.

Table 4.1 Optical asymmetric logic gates with p_p= 0.88 with varying gain at core 1

Port A	**Port B**	$X_{12}(dB)$	**Port C**	$X_{21}(dB)$	**Port D**
0	0	0	0	0	0
0	1	0.8062	1	-0.8062	1
1	0	-0.8062	1	0.8062	1
1	1	10.26	1	-10.26	0
			OR gate		XOR gate

Table 4.2 Optical asymmetric logic gate with p_p= 2.86 with varying gain at core 1

Port A	**Port B**	$X_{12}(dB)$	**Port C**	$X_{21}(dB)$	**Port D**
0	0	0	0	0	0
0	1	-10.48	0	10.48	1
1	0	10.48	1	-10.48	0
1	1	1.961	1	-1.961	0
					D = $\bar{A}$.B

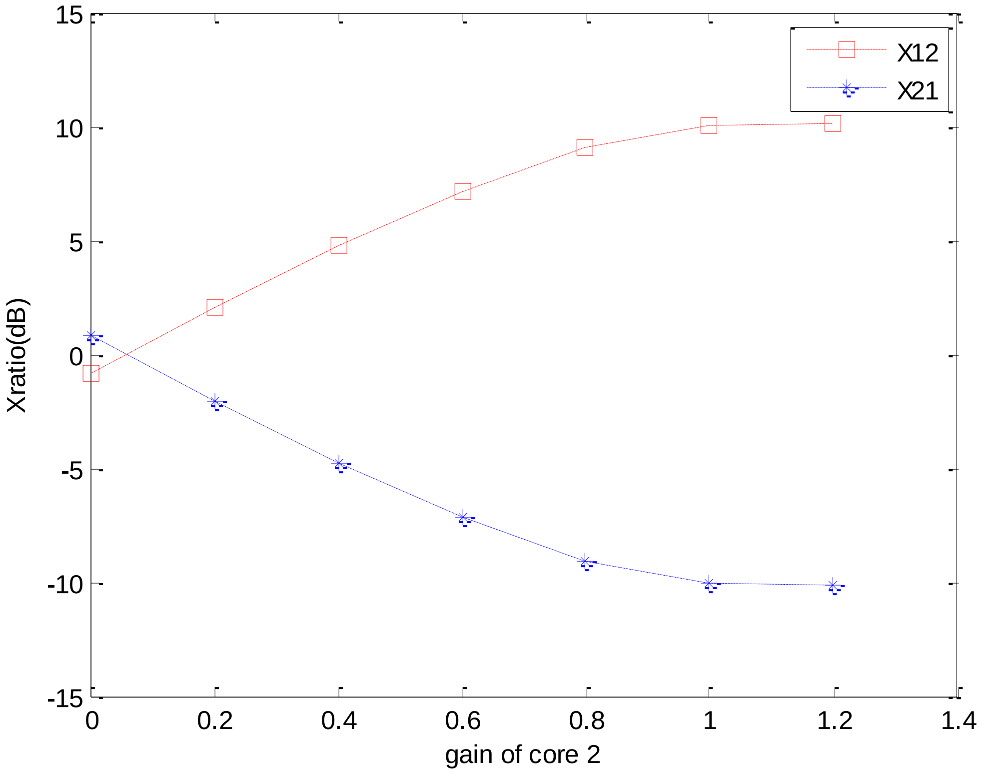

Figure 4.16 The Xratio level as a function of gain at core 2 when p_p= 0.88 and $P_{10} = P_{20} = 1$ mW

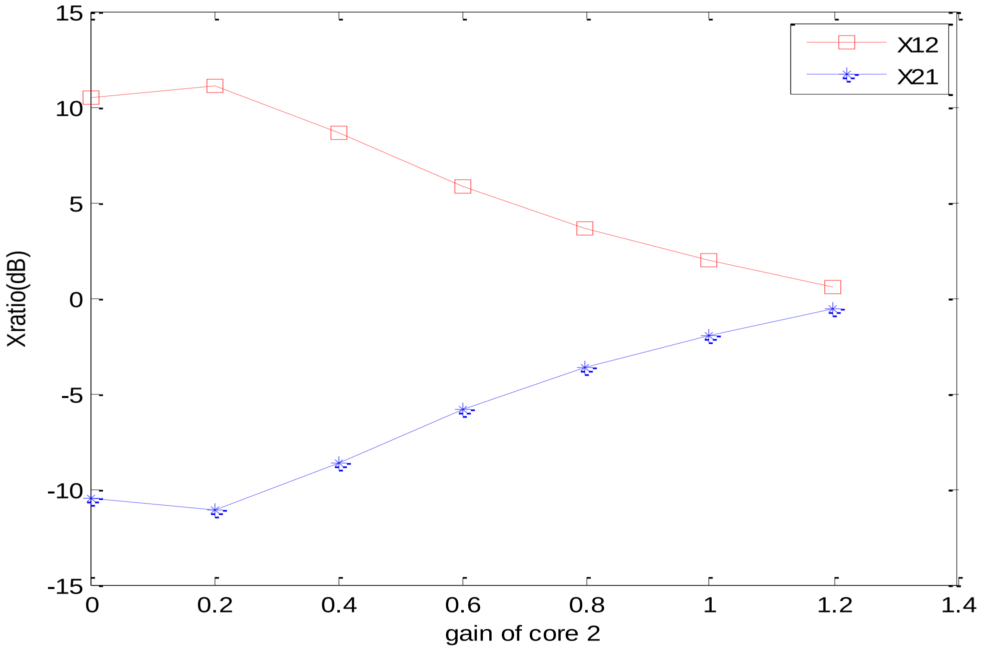

Figure 4.17 The Xratio level as a function of gain at core 2 when p_p= 2.86 and $P_{10} = P_{20} = 1$ mW

Now we study the effect of different values of gain of core 2 on the extinction ratio. We discuss two situations when p_p< 1 and p_p> 1 for analysing extinction ratio when p_p= 0.88 and p_p= 2.86. From fig. 3, we observe that X_{12} has maximum value of 10.13 dB for gain of 1.2 and X_{21} has minimum value of -10.13 dB for gain of 1.2. From fig. 4, we observe that X_{12} has maximum value of 11.14 dB for gain of 0.2 and X_{21} has minimum value of -11.14 dB for gain of 0.2.

Next we study the influence of different gain on the Boolean operation of coupler. The gain values (g = 0.2 and g = 1.2) have been selected in a way to provide the best average values of Xratio for the configurations (0,1), (1,0) and (1,1), so it is easy to judge the logic gates. From tables 1 and 2, it can be seen that an OR gate, a XOR gate and a new logic expression D = $\bar{A}.B$ has been realized.

Table 4.3 Optical asymmetric logic gates with p_p= 0.88 with varying gain at core 2

Port A	**Port B**	$X_{12}(dB)$	**Port C**	$X_{21}(dB)$	**Port D**
0	0	0	0	0	0
0	1	0.817	1	-0.817	1
1	0	-0.817	1	0.817	1
1	1	3.698	1	-3.698	0
			OR gate		XOR gate

Table 4.4 Optical asymmetric logic gate with p_p= 2.86 with varying gain at core 2

Port A	**Port B**	$X_{12}(dB)$	**Port C**	$X_{21}(dB)$	**Port D**
0	0	0	0	0	0
0	1	-10.5	0	10.48	1
1	0	10.5	1	-10.48	0
1	1	3.356	1	-1.961	0
					D = $\bar{A}$.B

CHAPTER 5

Conclusions

A scheme of all-optical logic gates centred upon the nonlinear fiber coupler with XPM of pump is proposed. In the scheme, signals with lower power input from the two ports, respectively, and the pump and one of two signals are coupled into a certain channel by WDM. By using the analytical method, the coupled nonlinear Schrödinger equations is solved, and the switching characteristics of the nonlinear coupler with the cross- phase modulation is obtained. A study of extinction ratio (Xratio) of the device is done. The extinction ratio of a switch is defined as the ratio of the on state output power to the off state output power. We draw the following conclusions from our thesis:

1. By increasing the value of coupling coefficient K, the maximum value of transmission coefficient for core 1 decreases and the minimum value of transmission coefficient for core 2 increases.
2. By increasing the value of K, the input power for peak value of transmission coefficient also increases.
3. By increasing the value of coupling coefficient from 0.05 to 0.1 the graphs for pump power $p_p< 1$ and $p_p> 1$ are reversed.
4. We study the effect of different values of gain of core 1 and core 2 on the extinction ratio. It can be seen that an OR gate, a XOR gate and a new logic expression D = $\bar{A}.B$ has been realized.

Future Scope

- The performance of all-optical logic gates based on fiber coupler can be analysed in presence of random dispersion.
- The work can be further extended in study of three core couplers and multi core couplers in presence of random dispersion

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List of Publications

1. Research paper titled “Effect of coupling coefficient on the switching characteristics of a Nonlinear Directional Coupler” published in OPTO-2015 organized by Optical Society of America (OSA)
2. Research paper titled “Analysis of the effect of coupling coefficient in a Nonlinear Directional Coupler based on cross-phase modulation” published in International Journal for Innovative Research in Science and Technology
3. Research paper titled “Study of logic gates in a gain induced Nonlinear Directional Coupler” communicated in Microwave and Optical Technology Letters