PERFORMANCE ANALYSIS OF NONLINEAR DIRECTIONAL FIBER COUPLER IN PRESENCE OF RANDOM DISPERSION”

Dissertation submitted in the partial fulfilment of
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DECLARATION

I, Sukhwinder Singh, hereby declare that the work, which is being presented in this dissertation entitled **"Performance Analysis of Nonlinear Directional Fiber Coupler in Presence of Random Dispersion"** 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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This is to certify that the above statement made by the student is correct to the best of my knowledge and belief.

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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 Soliton switching characteristics of nonlinear directional fiber coupler in presence of Kerr nonlinearity and fifth order nonlinearity. The soliton pulse is used because it gives more efficient switching characteristics and also in future we have commercial optical soliton communication systems. The detrimental effect of quintic nonlinearity on switching dynamics of NLDC has been investigated. We also analyzed the switching characteristics in presence of third order dispersion in addition to group velocity dispersion.

In practical optical systems, random dispersion can occur due to variation in core cladding diameter or fluctuations in carrier doping density and other factors like thermal stress. The random dispersion becomes important as quality of transmission increases. We investigated the switching characteristics of nonlinear fiber directional coupler in presence of random dispersion in real time conditions. To analyze it in more practical scenario, we considered the effects of Intrapulse Raman scattering, self steepening, third order dispersion, Intermodal dispersion along with Kerr nonlinearity and Quintic nonlinearity. We analyzed the switching dynamics by varying random dispersion in our system from 5 percent to 30 percent. The evolution of soliton pulse and respective contour plots are also studied. We found the tolerance limit in random dispersion with which NLDC gives faithful switching characteristics which would be helpful to designer of Fiber Couplers.

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CHAPTER 1

Introduction to Optical Switching Devices

1.1 Optical Switching Systems

The switching operation is one of the crucial functions of all information processing or information transmission systems. Some of them like communication network or computer are generally composed of connected switches. Most networking equipment is based on electronic-signals, meaning that the optical signals have to be converted to electrical signals, amplified, regenerated or switched, and then reconverted to optical signals. This is generally referred to as an 'optical to-electronic-to-optical' (OEO) conversion and is a significant bottleneck in transmission of data. The large amounts of information propagating around an optical network needs to be switched through various points known as nodes. The traditional way to switch the information is to first detect the light from the input optical fibers, convert it to an electrical signal, and then convert that back to a light signal, which is then sent down the fiber we want the information to go on. For example, in a long-haul network, an OEO conversion may occur as often as every 600 kilometres just for amplification purposes. The basic advantage of Optical Switching is that by replacing existing electronic network switches with optical ones, the need for OEO conversions is removed. The advantages are significant. 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 possibility to avoid multiple conversions of information from a photonic to electronic form to provide switching at subsequent nodes of network .All optical switching devices can give this chance. Generally an all optical switching operation occurs when output characteristics of device can be determined by parameters of input signal or by a separate control beam. The optical switching could be done by number of devices, first group of 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. Second group relies on optically induced changes in phase difference between two pulses. The very important device which can perform all optical switching is fiber coupler.

1.2 Coupled Mode Devices: Waveguide Directional Coupler

Coupled mode devices are based on power exchange between two modes propagating in a wave guiding system. Typically at higher power the nonlinear index change spoils the phase matching between the modes and therefore changes the power exchange rate. Coupling, being a subject of optical control can occur between modes of two adjacent waveguides coupled by overlapping evanescent fields as well as between two orthogonally polarised modes of the same waveguide. A 2x2 waveguide directional coupler consists of two closely placed parallel single-mode optical waveguides. The basic operation of waveguide coupler is a partial or complete transfer of power between the two waveguides. The optical interaction can also be viewed as the beating between the symmetric and the anti-symmetric super modes of the device structure. The uniformly spaced parallel interaction region plays the key role in the coupling process. The interaction region has a longitudinally invariant structure and the optical coupling that takes place in this region can be understood through the coupled mode analysis. In the coupled mode analysis across the interaction region, the two uniform waveguides placed parallel to each other are assumed as a composite structure. The composite system formed by the two single-mode waveguides can support two modes, a symmetric (even) mode and an anti-symmetric (odd) mode. These two modes called the normal modes or super-modes of the composite structure have different propagation constants. When light is launched into one of the optical waveguides, it excites a linear combination of the symmetric and the anti-symmetric super modes. Because of the unequal propagation constants of the two modes, the fields propagating down the system develop a relative phase difference with the distance of propagation. For a certain length of interaction, if the accumulated phase difference between these two modes becomes π, the superposition of these two modal fields will result in the cancellation of the field amplitudes in the input waveguide and an addition in the second waveguide. Such a situation is referred to as coupled state, and the corresponding interaction length as the coupling length (L_c). If the interaction length or length of waveguide coupler extends beyond coupling length, coupling takes place in opposite direction from the second waveguide at the input waveguide. Thus propagation distance of $2L_c$ results in accumulated phase difference of 2Π. Hence power will be transferred back in input waveguide. Thus a periodic exchange of power between the two waveguides takes place with propagation. If case of identical waveguides, complete power can be transferred from one waveguide to the other and vice-versa, while for non-identical waveguides, only a certain maximum power transfer takes place.

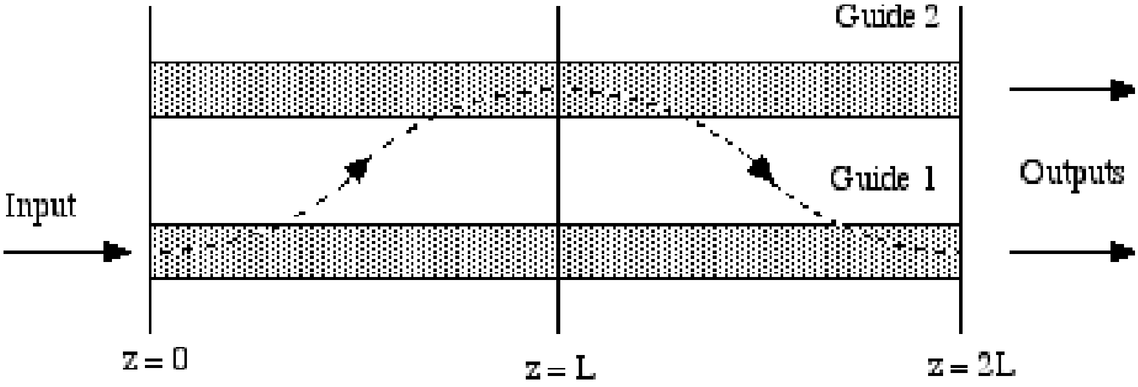


Fig.1.1. Coupling process showing transfer of power as function of length of coupler [31]

Fig.1.1 shows a waveguide coupler consisting of two waveguide which are in close proximity over a length L .if the input power $P_1(0)$ is launched in waveguide 1 and periodic exchange of power takes place between the waveguides along the length of coupler as shown in Fig 1.1.

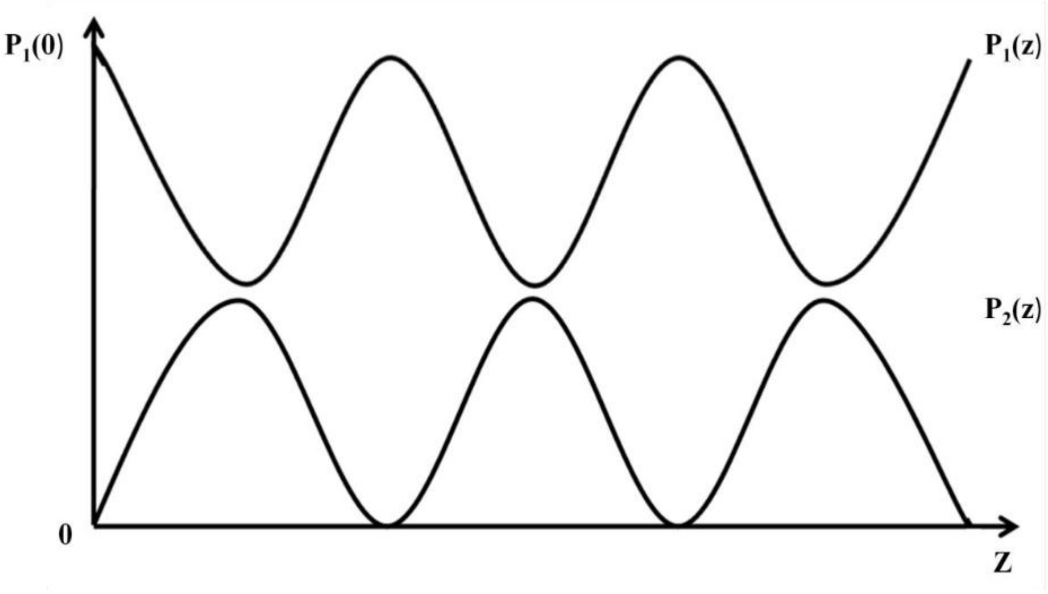


Fig.1.2 Periodic exchange of power between guides 1 and 2 [49]

The modal field of single waveguide varies as z in form $e^{i\beta 1z}$, the amplitude of mode at distance z in form of a(z) is

$$da/dz = -i\,\beta_1 a \qquad (1.2.1)$$

where β_1 is the propagation constant in waveguide 1.if b(z) is amplitude of mode in waveguide 2, we get

$$db/dz = -i\,\beta_2 b \qquad (1.2.2)$$

When both waveguide are in close proximity then the modes in the two wave guide interact through the evanescent field. So the variation of amplitude of the modes in two waveguides is

$$da/dz = -i\beta_1 a - i\,k_{12} b(z) \qquad (1.2.3)$$

$$db/dz = -i\beta_2 b - i\,k_{21} a(z) \qquad (1.2.4)$$

Where the constant k_{12} and k_{21} represent the strength of interaction between the two modes and are known as coupling constant. The coupling constant depends upon the waveguide parameters like separation between the waveguides and operating wavelength. Suppose there exist wave in system with phase constant β.

$$a(z) = a_0 e^{-\beta z} \qquad (1.2.5)$$

$$b(z) = b_0 e^{-\beta z} \qquad (1.2.6)$$

By substituting (1.2.5) and (1.2.6) in (1.2.3) and (1.2.4), we get

$$a_0(\beta - \beta_1) - k_{12} b_0 = 0 \qquad (1.2.7)$$

$$b_0(\beta - \beta_1) - k_{21} a_0 = 0 \qquad (1.2.8)$$

The nontrivial solution of (1.2.7) and (1.2.8) will be

$$B_{s,a} = \frac{\beta_1 + \beta_2}{2} \pm \left[\frac{1}{4}\,(\beta_1 - \beta_2)^2 + k^2\right]^{\frac{1}{2}} \qquad (1.2.9)$$

Thus in coupled waveguide system we have two independent set of modes, one propagating with a propagation constant β_s and the other with β_a. Therefore the general solution of equation (1.2.3) and (1.2.4) can be written as

$$\mathrm{A(z)} = a_s e^{-\beta_s z} + a_a e^{-\beta_a z} \qquad (1.2.10)$$

$$\mathrm{B(z)} = \ (\beta_s - \beta_1)\ a_s e^{-\beta_s z}\ /k_{12}\ \ +(\beta_a - \beta_1)\ a_s e^{-\beta_s z}\ /k_{12} \qquad (1.2.11)$$

The power in waveguide 1 and 2 is proportional to| a(z)|^2 and |b(z) |^2 . We get from (1.2.10) and (1.2.11)

$$|a(z)|^2 = 1 - \frac{4k^2}{\Delta\beta^2+4k^2}\ sin^2[(\frac{1}{4}\Delta\beta^2 + k^2)^{1/2} z] \qquad (1.2.12)$$

$$|b(z)|^2 = \frac{4k^2}{\Delta\beta^2+4k^2}\ sin^2[(\frac{1}{4}\Delta\beta^2 + k^2)^{1/2} z] \qquad (1.2.13)$$

The coupling length is given by

$$L_c = \frac{\pi}{2}\ (\frac{1}{4}\Delta\beta^2 + k^2)^{1/2} \qquad (1.2.14)$$

The complete energy transfer take place when propagation constants in both the waveguide are equal and coupling length becomes

$$L_c = \pi/2k \qquad (1.2.15)$$

The power distribution between two waveguides is shown in Fig.(1.3)

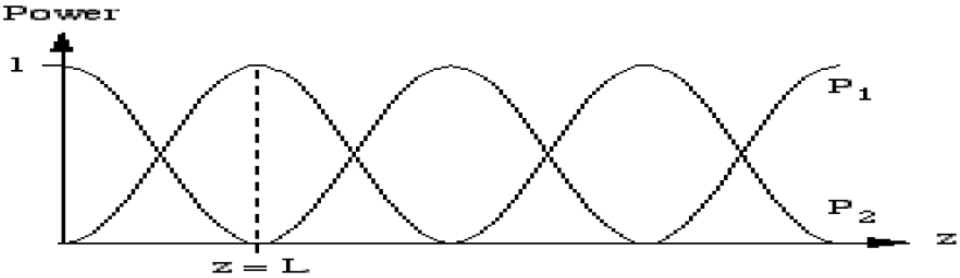


Fig.1.3. Power distribution between two coupled waveguides as function of distance[49]

We can see that power distribution between two waveguides is oscillatory but is periodic with complete power transfer taking place at integral multiples of coupling length.

1.3 Optical Solitons

Optical Soliton is special wave which is special wave which maintains its shape as it travels through optical fiber. Solitons waves are formed by cancellation of non- linear and dispersive effects in the medium. Hasegawa and Tappert were the first theoretically predicting the existence of optical solitons in fibers, and they were experimentally verified by Mollenauer in 1980. Dispersion is the phenomenon in which the phase velocity of a wave depends on its frequency. Every wave form considered as consisting of plane waves of several different frequencies. Due to dispersion different frequencies travel with different speed and due to propagation delays shape of pulse changes over time. Dispersion does not add new frequencies in spectra but arrange phase relation between existing ones. On the other hand, nonlinear effects like Kerr effect modify the phase shift across the pulse and thus create new frequency components in the spectra of the pulse frequencies. The nonlinear effects should exactly balance to produce pulse with constant shape which is a soliton.

Solitons are of two types: Temporal Soliton - These are pulses that will not change their shape because the nonlinear effects will balance the dispersion.
Spatial Soliton – In these the nonlinear effects balance the diffraction. The field can change the refractive index of the medium while propagating. If the field is also a propagating mode of the guide it has created, then it will remain confined and it will propagate without changing its shape. Fig.1.4. shows the balance between nonlinear kerr effect and group velocity dispersion effect. The dispersion is anomalous, so that the higher frequency components will propagate a little faster than the lower frequencies, thus arriving before at the end of the fiber and we get is a wider chirped pulse. Considering nonlinear effects that at the beginning of the pulse the frequency is lower and at the end it is higher. After the propagation through medium, we will get a chirped pulse with no broadening because dispersion is not considered. It is possible to make a pulse so that the two effects balance each other. At higher frequencies, dispersion will try to let them propagate at high speed, while nonlinear Kerr effect will slow them down. The overall effect will be that the pulse does not change its shape while propagating in medium called temporal solitons.

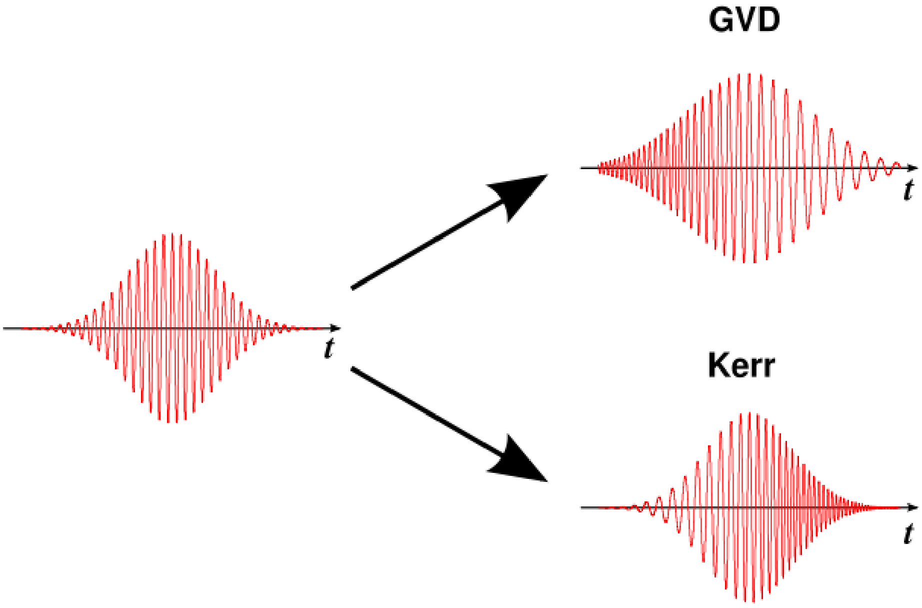


Fig.1.4. Linear and nonlinear effects on Gaussian pulse in optical fiber [50].

The fundamental soliton can be defined as

$$p(t) = \text{sech}\,(A\tau)$$

Fig.1.5. shows the shape of fundamental soliton as it propagates in the fiber.

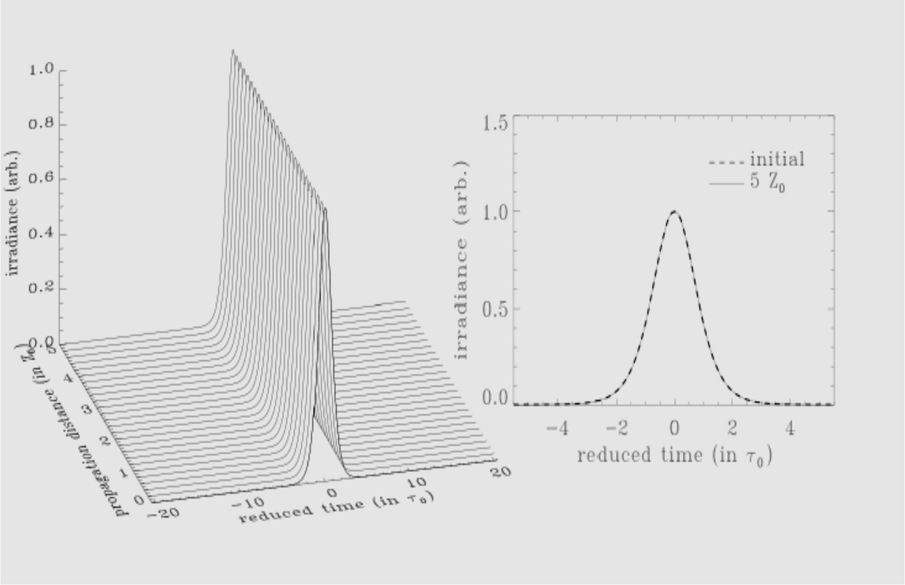


Fig.1.5 Optical soliton intensity profile as function of propagation distance in presence of nonlinear and dispersive effects [5]

Spatial Solitons can be formed by maintaining balance between linear diffraction and nonlinear self focussing as shown in Fig.1.6. Self focussing is possible with media with nonlinear effects like Kerr effect. We know refractive index depends on intensity so the refractive index depends on position in space.

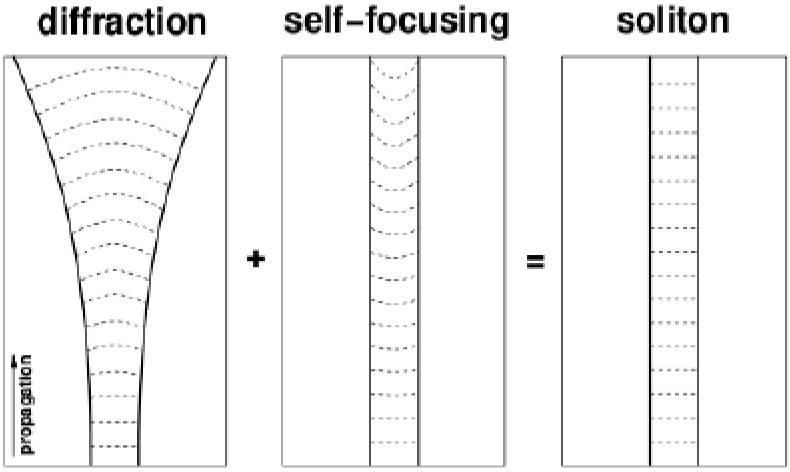


Fig.1.6 Formation of Spatial Solitons [50].

It has been demonstrated that spatial solitons are stable even in presence of small amplitude and phase perturbations.

1.4. Motivation and Goal of Work

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. The goal of this work is to investigate performance of nonlinear directional fiber coupler in presence of quintic nonlinearity, coupling coefficient dispersion, third order dispersion, intrapulse Raman scattering and self steepening effects. Our goal is to find range of values in which optical fiber coupler performs efficient switching operation. In practical systems, optical fiber face random dispersion due to material imperfections and medium imperfections .The goal of our work is to investigate the effect of random dispersion on performance of nonlinear directional fiber coupler and to find out allowed tolerance in random dispersion to help designer of fiber coupler.

1.5. Outline of Dissertation

The following are main objectives of this Dissertation:

1. To analyze the performance of Nonlinear Directional Fiber Coupler in Kerr nonlinear medium considering quintic nonlinearity.
2. To analyze effects of Third order Dispersion in fiber coupler in cubic-quintic nonlinear optical medium.
3. To analyze Soliton Switching in Nonlinear Fiber Directional Coupler in Presence of Random Dispersion and higher order nonlinear effects.

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 Random Dispersion and higher order nonlinear effects.

Chapter 5 describes conclusion and future scope of our work

CHAPTER 2

Nonlinear and Linear Effects in Fiber Coupler

2.1 Nonlinear Directional Fiber Coupler

Fiber couplers are extremely important components in Optical fiber technology. Nonlinear directional coupler has been broadly investigated due to its applications in switching, computing, fiber optic sensing and so on. They are generally four port devices and their operation relies on distributed coupling between waveguides in close proximity. The main use of fiber and integrated coupler is power splitter that is fiber optical equivalent of free space beam splitter. The directional coupler is a device consisting of two parallel single mode optical fiber cores .The transfer of optical power between the modes of the two cores of the coupler is explained as evanescent field coupling between the modes of the individual cores of the coupler. The mechanism is characterized by a parameter known as the coupling coefficient. Since the output is directed in one of the two different directions, such devices are known as directional fiber couplers or simply directional couplers.

Their full name nonlinear directional couplers (NLDC) are due to the fact that they exhibit nonlinear phenomena of Kerr type. The optical fiber is a very thin transparent thread which owns driving data in form of light pulses. Being Cylindrical geometry , it is composed of a core of refractive index n_1 of a diameter, surrounded by a cladding of index n_2, all wrapped in a plastic coating as shown in Fig. 2.1.

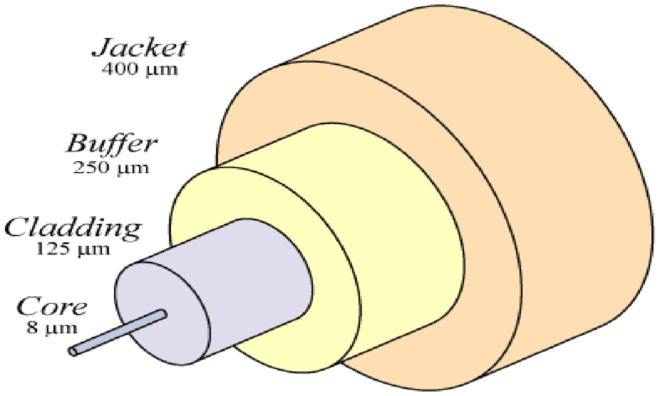


Fig.2.1. Optical fiber cable

By evanescent coupling, the channels switch between optical cores with a period that depends on their wavelength. At higher light intensities, there are nonlinearities in the optical fiber coupler. Higher optical intensities detune the coupler, and induce changes in the refractive index with $n = n_0 + n_2 I$, where n_0 is the refractive index at low light intensities, n_2 is the Kerr nonlinear coefficient, and I is the light intensity.

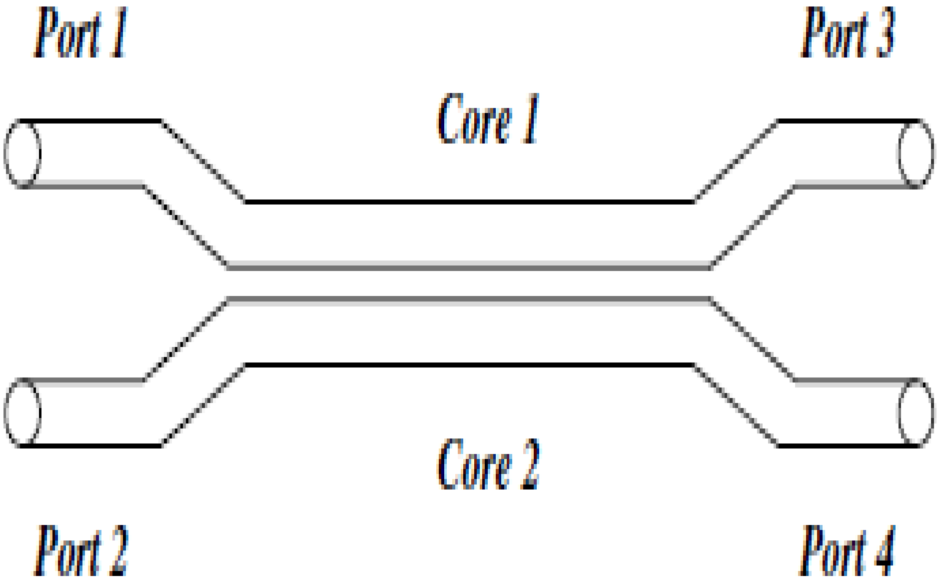


Fig.2.2. Nonlinear Directional Coupler (NLDC) [39]

The pulse switching in NLDC could be of two types. The first one is a power-controlled switching in which the output is a function of the input power in one channel. The second type of switching is known as phase-controlled switching which may be considered as an attractive alternative of power-controlled switching. In Phase controlled switching the phase difference between a weak and a strong input signal governs the switching dynamics.

2.2 Nonlinear Effects

2.2.1 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 phenomenons like self focussing, Self phase modulation and modulation instability.

2.2.2 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 analyze 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.

2.2.3 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 $\beta 3$ term 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 $\beta 2$ 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 β_3 is third order dispersion factor.

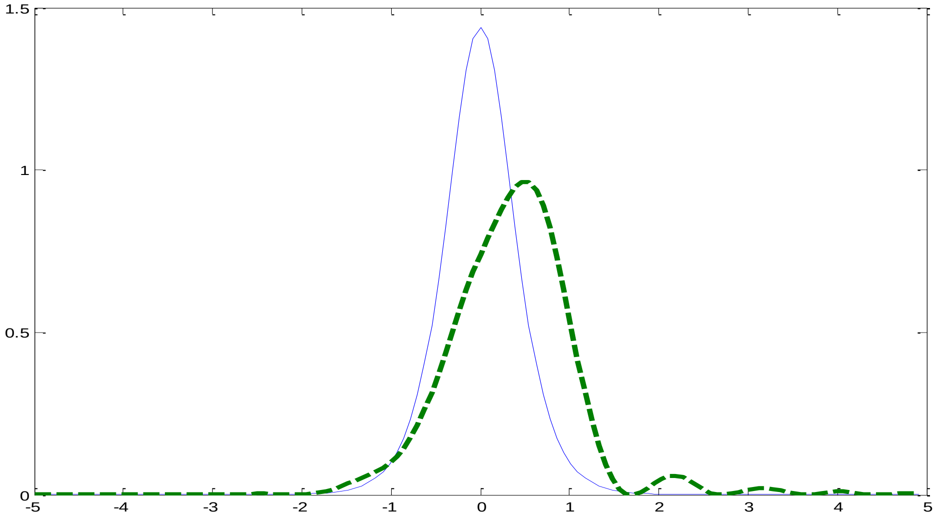


Fig.2.3. Effect of third order dispersion on pulse shape

Fig.2.3. shows effect of third order dispersion on pulse propagation .As the pulse moves its shape changes with oscillations at trailing edge.

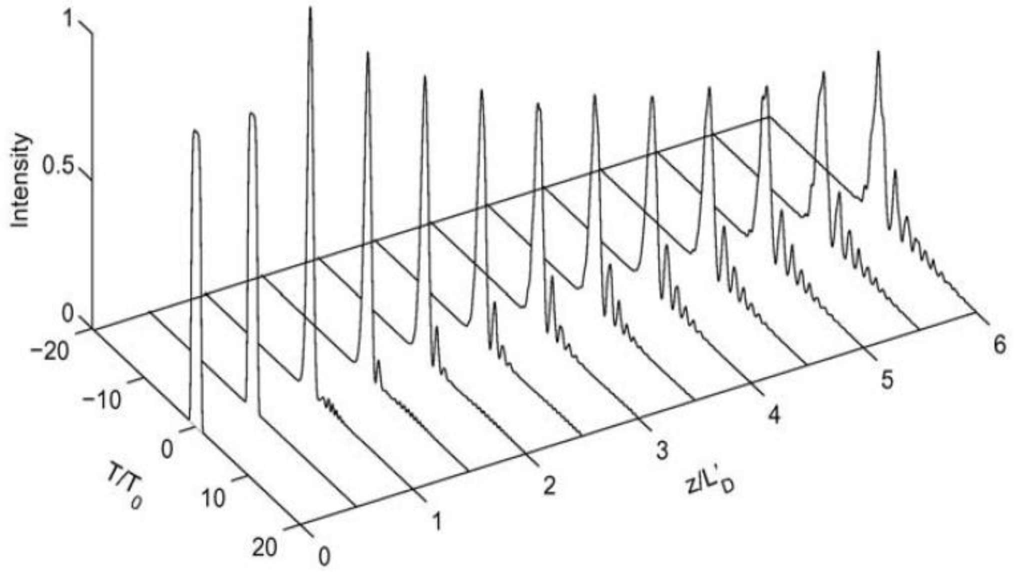


Fig.2.4. Evolution of super Gaussian profile in presence of third order dispersion [5]

2.2.4 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 pulse pump the low frequency components of the same pulse by stimulated Raman scattering thereby transferring energy to low frequency components as pulse spectrum shifts the pulse speed decreases due to group velocity dispersion.Fig.2.5. shows IRS effect as pulse propagates in optical fiber. 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.

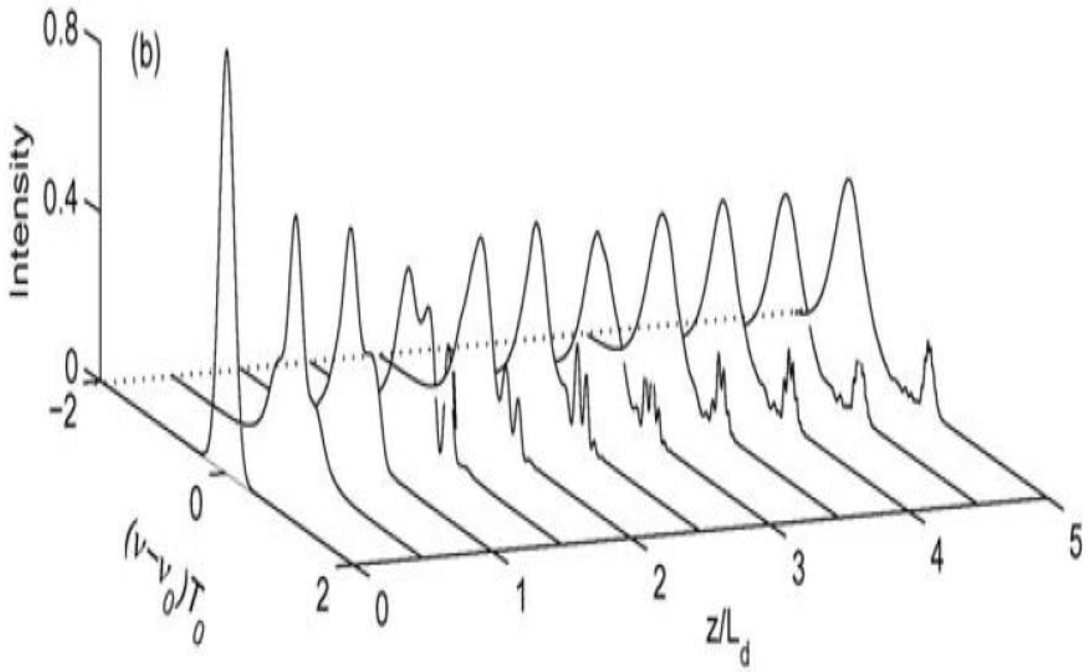


Fig.2.5. Intrapulse Raman scattering effect on pulse evolution

2.2.5 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.

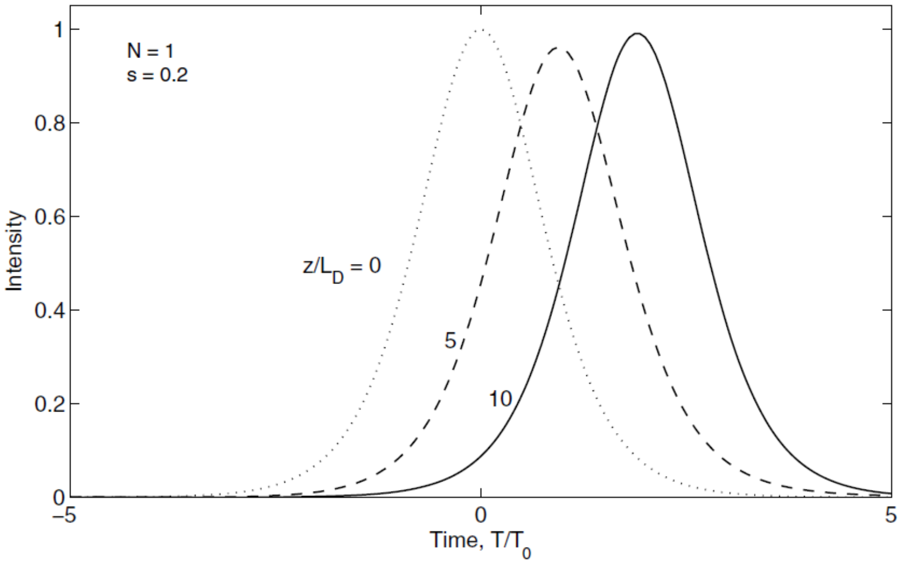


Fig.2.6. Effect of self steepening on pulse shape as propagation distance increases.

2.3 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**.**

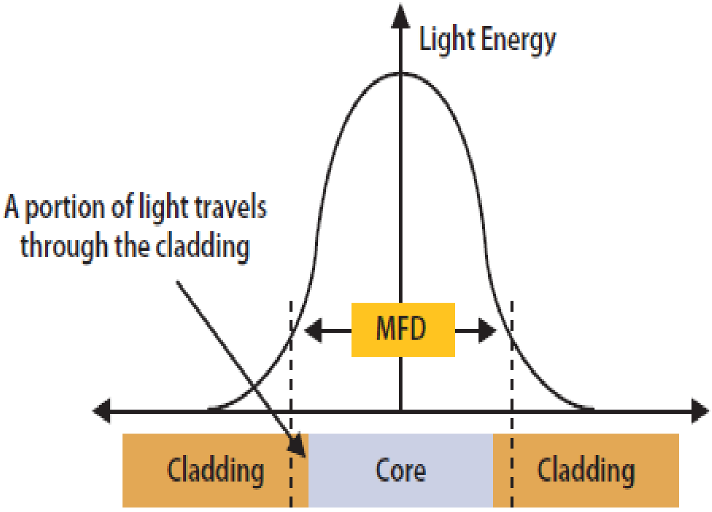


Fig 2.7. Mode field diameter of optical fiber

2.3 Nonlinear Schrödinger Equation

To describe the propagation of light signals in optical fibers nonlinear Schrödinger 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

$$\nabla \mathrm{X} \mathrm{E} = -\frac{\partial \mathrm{B}}{\partial \mathrm{t}} \tag{2.3.1}$$

$$\nabla \mathrm{X} \mathrm{H} = \frac{\partial \mathrm{D}}{\partial \mathrm{t}} \tag{2.3.2}$$

$$\nabla . \mathrm{D} = 0 \tag{2.3.3}$$

$$\nabla . \mathrm{B} = 0 \tag{2.3.4}$$

Taking curl of equation (2.3.1) we get

$$\nabla \mathrm{X} \nabla \mathrm{X} \mathrm{E} = \nabla \mathrm{X} \left(-\frac{\partial \mathrm{B}}{\partial \mathrm{t}}\right) = -\frac{\partial}{\partial \mathrm{t}} (\nabla \mathrm{X} \mathrm{B}) \tag{2.3.5}$$

$$\nabla \mathrm{X} \nabla \mathrm{X} \mathrm{E} = -\mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2} - \mu_0 \frac{\partial^2 P}{\partial t^2} \tag{2.3.6}$$

Now using mathematical identity

$$\nabla \mathrm{X} \nabla \mathrm{X} \mathrm{E} = \nabla(\nabla . \mathrm{E}) - \nabla^2 E \tag{2.3.7}$$

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

$$\nabla^2 E - \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} = \mu_0 \frac{\partial^2 P}{\partial t^2} \tag{2.3.8}$$

The induced polarization is given by

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

Here 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

The equation (2.3.8) becomes

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \mu_0 \frac{\partial^2 (P_{LIN})}{\partial t^2} + \mu_0 \frac{\partial^2 (P_{NONLIN})}{\partial t^2} \tag{2.3.9}$$

The electric field is in terms of frequency given by

$$\boldsymbol{E} = E_0 e^{j\omega_0 t} \tag{2.3.10}$$

Fourier transform of E is given as

$$\widetilde{\boldsymbol{E}}(r, \omega - \omega_0) = \int_{-\infty}^{\infty} \boldsymbol{E}(\mathrm{r}, \mathrm{t})\, e^{-j(\omega-\omega_0)t} dt \tag{2.3.11}$$

The wave equation becomes

$$\nabla^2 \tilde{E} + \epsilon(\omega) k_0^2 \tilde{E} = 0 \tag{2.3.12}$$

Where $\epsilon(\omega) = 1 + \chi^{(1)}(\omega) + \epsilon_{NL}$

Now the signal equation is given as

$$\widetilde{\boldsymbol{E}}(r, \omega - \omega_0) = F(\rho, \varphi) \widetilde{\boldsymbol{A}}(z, \omega - \omega_0) e^{-j\beta_0 z} \tag{2.3.13}$$

Where $\widetilde{\boldsymbol{A}}(z, \omega - \omega_0)$ is envelope function.

By substituting function in wave equation and separating in two parts

$$\nabla_{\perp}^2 \mathrm{F} + \{ \epsilon(\omega) k_0^2 - \tilde{\beta}^2 \} \mathrm{F} = 0 \tag{2.3.14}$$

$$-2j\beta_0 \frac{\partial \widetilde{\boldsymbol{A}}}{\partial z} + (\tilde{\beta}^2 - \beta_0^2) \widetilde{\boldsymbol{A}} = 0 \tag{2.3.15}$$

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

$$\widetilde{\beta}^2 - \beta_0^2 \approx 2\beta_0(\widetilde{\beta} - \beta_0) \tag{2.3.16}$$

Using Taylor series expansion, we get

$$\widetilde{\beta}(\omega) = \beta(\omega) + \Delta\beta(\omega) \tag{2.3.17}$$

And dielectric constant is given as

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

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 given

$$A(z,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}(z, \omega - \omega_0) e^{j(\omega-\omega_0)t}\, d\omega \tag{2.3.18}$$

Shifting in time domain , we have

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} - j\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2}A = -j\gamma|A|^2 A \tag{2.3.19}$$

which is Nonlinear Schrödinger 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.

λ is wavelength in nm

c is speed of light in vacuum

Aeff is effective area of core in mm2

n_2 can be calculated by equation

$$n = n_0 + n_2 I$$

2.4 Coupled Nonlinear Schrodinger Equations (CLNSE)

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

$$i\left(\frac{\partial A_1}{\partial Z} + K_1\frac{\partial A_2}{\partial T}\right) + \frac{P(r)}{2}\frac{\partial^2 A_1}{\partial T^2} - i\frac{\beta_3}{6}\frac{\partial^3 A_1}{\partial T^3} + \gamma|A_1|^2 A_1 + \gamma_2|A_1|^4 A_1 + \frac{i}{\omega_0}\frac{\partial}{\partial T}(|A_1|^2 A_1) - T_R A_1\frac{\partial |A_1|^2}{\partial T} = -K_0 A_2 \tag{2.4.1}$$

$$i\left(\frac{\partial A_2}{\partial Z} + K_1\frac{\partial A_1}{\partial T}\right) + \frac{P(r)}{2}\frac{\partial^2 A_2}{\partial T^2} - i\frac{\beta_3}{6}\frac{\partial^3 A_2}{\partial T^3} + \gamma|A_2|^2 A_2 + \gamma_2|A_2|^4 A_2 + \frac{i}{\omega_0}\frac{\partial}{\partial T}(|A_2|^2 A_2) - T_R A_2\frac{\partial |A_2|^2}{\partial T} = -K_0 A_1 \tag{2.4.2}$$

$$P(r) = \beta_2(1 + r) \tag{2.4.3}$$

Where A_1 and A_2 are slowly varying envelope amplitude in fiber core 1 and core 2 , respectively, γ is the kerr nonlinearity parameter, γ_2 is quintic nonlinearity parameter , β_2 is group-velocity dispersion (GVD) coefficient, β_3 governs the effect of third order dispersion(TOD), $\omega_0 = 2\Pi c/\lambda$ is the carrier frequency, K_0 and K_1 are zeroth order coupling coefficient and first order coupling constant dispersion coefficient. The seventh and eighth term in equation (1) and (2) takes into account self-steepening and intrapulse Raman scattering respectively. T_R is Raman response time. An NLDC consists of single mode fibers which are actually bimodal in nature that support two eigen modes, i.e. symmetrical and ant symmetrical modes. This leads to intermodal dispersion (IMD), which can significantly change the switching dynamics in the NLDC . The IMD can be captured via coupling constant dispersion in a coupled nonlinear Schrödinger equation as first order coupling constant dispersion coefficientK_1.

We can write coupled nonlinear Schrödinger equations in normalized soliton units as

$$i\left(\frac{\partial u}{\partial \xi}+\delta\frac{\partial v}{\partial t}\right)-\frac{1}{2}\frac{\partial^2 u}{\partial t^2}-i\delta_3\frac{\partial^3 u}{\partial t^3}+|u|^2u+\eta|u|^4u+is\frac{\partial}{\partial t}(|u|^2u)-\tau_R u\frac{\partial |u|^2}{\partial t} = -k_0 v \tag{2.4.4}$$

$$i\left(\frac{\partial v}{\partial \xi}+\delta\frac{\partial u}{\partial t}\right)-\frac{1}{2}\frac{\partial^2 v}{\partial t^2}-i\delta_3\frac{\partial^3 v}{\partial t^3}+|v|^2v+\eta|v|^4v+is\frac{\partial}{\partial t}(|v|^2v)-\tau_R v\frac{\partial |v|^2}{\partial t} = -k_0 u \tag{2.4.5}$$

Where, u, v are normalized slowly varying envelope amplitude in input (core-1) and its neighbouring (core-2). δ is first order coupling constant dispersion coefficient , s is coefficient of quintic nonlinearity which take negative sign in our study as we are interested in self-defocusing quintic nonlinearity. k_0 is normalized zeroth order coupling coefficient which is measure of strength of interaction between fiber cores. ξ is normalized distance and t is normalized time. $\delta_3 = \beta_3/6\beta_2 T_0$ governs third order dispersion effect. The parameters ρ and τ_R are self steepening and intrapulse Raman scattering respectively are defined as

$$s = \frac{1}{\omega_0 T_0}\ ,\ \tau_R = \frac{T_R}{T_0}$$

where T_0 is initial pulse width.

CHAPTER 3

Literature Survey

The Optical fiber coupler is first introduced by S.M Jenson [1] in his classical paper in 1982.He designed a nonlinear coherent coupler which could be used for future optical processing at a very fast data rates. It was based on the coherent interaction of two optical waveguides placed close to each other because of evanescent field overlap. The nonlinear interactions change the power transfer to give strong nonlinear transmission characteristics. This device could be fabricated by conventions techniques for integrated optic switches.

G. I. Stegeman, E. M. Wright, N. Finalyson, R. Zanoni , and C. T. Seaton studied the advancements in third order nonlinear optics[2]. All integrated optics devices such as directional couplers, Mach-Zehnder interferometers, prism couplers can be used as all optical signal processing .They demonstrate experimental and theoretical results on operating characteristics of these devices. They also discussed measurement techniques which could be used to evaluate nonlinearities in waveguides.

P. M. Ramos and C. R. Paiva [3] in their paper shows 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.

Stefan trillo, Stefan wabnitz, and George stegeman in their paper Nonlinear Propagation and Self-switching of Ultra short Optical Pulses in Fiber Nonlinear Directional Couplers [4] studied the propagation of short optical pulses in a nonlinear directional coupler which is operating in the normal dispersion regime. They use birefringent periodically rocked fiber filter where coupling occurs between the two orthogonally polarized modes. They show 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.

Sotiris droulias, Manos manousakis, Kyriakos hizanidis [6] investigated the Switching dynamics in nonlinear directional fiber couplers with intermodal dispersion. They use coupled nonlinear Schrodinger equations (CNLSE) of the coupled-mode theory as mathematical model .They discuss relationship between this model with the normal-mode theory. Numerical simulations are performed and effect of IMD on transmission is investigated. They showed that As long as IMD is kept weak the propagation of the solitons is slightly distorted. The result is that even when IMD is present the system remains faithful up to a certain value for the IMD parameter.

Youfa Wang and Jianhua Liu in their paper “All-Fiber Logical Devices Based on the Nonlinear Directional Coupler” [7] 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.

Yuntuan Fang, Jun Zhou[8] in their paper investigated Effects of third-order dispersion on soliton switching in fiber nonlinear directional couplers. The third order dispersion effects increases by increasing third order dispersion coefficient and it is studied by split step fourier method .it has been found out that switching characteristics distort by third-order dispersion and it could be compensated by increasing higher order nonlinear effects.

Amarendra K. Sarma in his paper titled “Dark soliton switching in an NLDC in the presence of higher-order perturbative effects” [9] investigated soliton switching in a nonlinear directional coupler in the presence of intermodal dispersion, cross-phase modulation (CPM), third-order dispersion, Raman effect, and self-steepening effect. He showed that except cross phase modulation all other higher order effects have not much impact on switching of dark soliton through nonlinear directional coupler which is an improvement over bright soliton switching .Dark soliton even remains stable in presence of cross phase modulation even though it increases critical power of switching.

Qiliang Li , Yuyong Xie, Yinfang Zhu, Sheng Qian[10] analyzed Soliton switching and propagation in two-core nonlinear fiber coupler with high order coupling coefficient. They consider effect of both first order and second order coupling coefficient. They use variational method and split step fourier method to study transmission and switching characteristics of solitons in NLDC.They found that second order coupling coefficient reduces the coupling length, switching characteristics becomes sharper and threshold power of switching increases. Both results agree with variational analysis and numerical analysis.

Qiliang Li, Yuyong Xie, Yinfang Zhu, Yongmin Qi, and Zhijing Zhao [11] investigate effects of linear gain coefficient ,finite gain bandwidth and second order coupling coefficient on switching and transmission characteristics of fiber coupler. They study theoretically and use split step fourier method to study transmission and switching characteristics of nonlinear fiber coupler. They found both second-order coupling coefficient dispersion and the finite-gain bandwidth degrade the switching characteristics. the finite-gain bandwidth of linear gain suppresses significantly the pulse compression and amplification caused by the linear gain coefficient. It also suppresses the frequent pulse shape changes on pulse propagation caused by the second-order coupling coefficient dispersion.

Youfa Wang and WenFeng Wang in their paper titled"A Simple and Efficient Numerical Method for Nonlinear Pulse Propagation in N-Core Optical Couplers" [12] formed a set of n differential equations for N core coupler and they designed a algorithm that solves the equations in very efficient manner for pulse propagation involving loss, gain, higher order dispersion and coupling coefficient .This method is based on split step fourier method and very simple and accurate one.

Akira hasegawa and yuji kodama [13] studied signal transmission by optical soliton through optical fiber. A transmission rate of 1 Tbps is achieved per 30 km using envelope solitons having peak power of 1 W in single mode optical fiber. In optical soliton bit rate is limited by fiber loss and input power. The condition to obtain optimum performance are theoretically predicted

Bhambri k , N gupta [14] studied dispersion managed solitons up to distance of 54000 km link .They studied Dispersion management in optical solitons which is a promising way to increase transmission capacity of optical soliton based communication systems. They found successful transmission up to 54000 km with bit error rate of 6.2754* 10^{-013} which is a good transmission rate.

K. M. Aghdami, M. Golshani and R. Kheradmand[15] in their paper studied the two dimensional discrete optical solitons which are used in switching and all optical gates.They used 2 d array of coupled optical cavities with kerr nonlinearity. It is driven by plane holding beam.They numerically studied optical bistability and and modulational instability and also 2-D discrete cavity solutions are simulated. The results showed switching on/off of solitons with Gaussian beams to control their positions.Soltion interactions and soliton-gaussian interactions are studied and all optical NOR, XNOR, and NAND gates are proposed.

Chen, Xiong-Wen [16] investigated the bending of optical solitons in nonlinear photonic crystal waveguides.They propagate solitons in waveguide bends .They found that solitons destroy after passing through conventional waveguide bends .But by using waveguide bends in two dimensional PC slabs and modifying the structure ,perfect transmission of optical solutions are realized. They also generalized the criteria to form waveguide bends with low reflection loss.

Pedaci, F, Barland, S., Caboche, E.,Genevet[17] in their paper propose an all optical delay line which is based on lateral drift of cavity solitons in microresonators.This is experimentally demonstrated and they also analyze performance and compare it with alternative methods which are based on decrease of group velocity in the vicinity of resonances .They showed that current limitations can be overcome using broader devices with tailored material responses.

Kato, M , Mori, Y.[18] in their paper study the behavior of the soliton self-frequency shift experimentally.They use Raman soliton pulses with different shifted wavelengths (10-120 nm) are induced by using a single pump source and a 5.0-km-long highly nonlinear fiber.They found that in spite of fact that that pump intensities and magnitude of frequency shifts are different ,the frequency shift ceases at same interaction lengths.Then the diverge due to chromatic dispersion of fiber. So they found actual interaction length for self-frequency shift of Raman solitons and proved their independence of pump intensities.

Lu Gao, Kelvin H. Wagner , and Robert R. McLeod [19] in their paper designed All-Optical Tb/s 3R Wavelength Conversion Using Dispersion-Managed Light Bullets which are 3+1 D optical solitons. The proposed wavelength converter can operate at a very-high-switching rate with simultaneous reshaping, retiming, and regenerating (3R) capabilities. This is based on the nonlinear interactions between dispersion-managed (DM) (3+1) dimensional optical solitons.This wavelength converter has very compact size and have potential applications in future optical time-division multiplexing (OTDM) and wavelength-division multiplexing (WDM).

R. Ganapathy, K. Porsezian, A. Hasegawa [20] investigated Soliton Interaction Under Soliton Dispersion Management. The dispersion management system is used for chirped solitons have been studied in detail. In phase and out of phase soliton interaction is studied extensively.They found interaction forces can be suppressed by choosing soliton parameters properly. They found after compensating fiber loss results in soliton amplification and it can be achieved efficiently by choosing soliton width properly.

Serak, Svetlana V. ,Tabiryan, Nelson V. , Peccianti, M. , Assanto [21] demonstrated all optical logic gates by using spatial solitons in azobenzene liquid crystalline cells because of their large nonlinearity for light localization and used trans-cis photoisomerization for all-optical external control.Spatial solitons have power in microwatts and 632.8 nm wavelength. The switching of spatial soliton beams is achieved at 4.9 nm with milliwatt of power levels.

Mitatha, S.,Piyatamrong, B., Tamee, K. ; Yupapin, P.P [22] proposed a new system of multifunction sensors .They use dark and bright solitons in Mach-Zehnder interferometer (MZI) switch. The coincidence between dark and bright soliton pair within the MZI can be arranged by using the phase controller. Both solitons are assumed to input in MZI ports coincidentally.The soliton states face phase changes after propagation through sensor/phase shifter unit and phase change recovery unit is provided by using phase related measurement device. A sensing application can be formed by using orthogonal soliton pairs.the solution power can be reduced to single photon power of 1 microwatt. The self calibration concept between signal and referencing arms of a MZI also discussed in their paper.

M. Uzunov,R. Muschall, M. Golles, Yuri S. Kivshar, B.A. Malomed, and F. Lederer [23] in their paper investigated optical pulse switching in nonlinear directional coupler.They demonstrate the merits and limitations of using variational approach to study power controlled and phase controlled switching.they propose a trail function that accounts for variable width, amplitude, phase, and chirp of the pulses. The Euler-Lagrangian equations for the pulse parameters are derived and solved. They found that power switching provide excellent results with beam propagation method .The criteria for optimum phase controlled switching is also obtained.

Gil Cohen [24] investigated Soliton interaction and stability in nonlinear directional fiber couplers theoretically and numerically. Using the Hamiltonian structure of the equations, a canonical perturbation theory is developed .The stable steady state regime of soliton is formed. He found two families of bound two-soliton states and their stability analysis showed that neither of these states is stable. For each of the state there are perturbations which are kind of stable and unstable types. The numerical simulations also agreed with the existence of two types of stable perturbations and two types of unstable perturbations are also observed .

T. I. Lakoba et al. [25] investigated the Solitons in nonlinear fiber couplers with two orthogonal polarizations. They consider a model of two coupled nonlinear optical fibers with two polarizations in each fiber. They consider polarization to be circular or linear.they use variational method to find stable soliton solutions. They found families of solitons with equal energies in each core and asymmetric solitons that for most of the energy concentrated in one core.

Francois Leo et al. [26] in their paper studied nonlinear Symmetry Breaking Induced by Third-Order Dispersion in optical fiber cavities.They demonstrate their results numerically, analytically and experimentally also. The nonlinear symmetry breaking is induced by broken reflection symmetry in an optical fiber system. They investigate the modulation instability regime and investigate the effect of the third-order dispersion on the asymmetry in dissipative structures. The third order dispersion is limited to lower than 0.1 ps^2 /km in experimental results.

N. V. Alexeeva,I. V. Barashenkov,Andrey A. Sukhorukov, and Yuri S. Kivshar [27] studied Optical solitons in PT -symmetric nonlinear couplers with gain and loss. They provide gain in one waveguide and loss in other waveguide. the Stability properties of the high- and low-frequency solitons are found to be completely determined by a single combination of the soliton's amplitude and the gain-loss coefficient of the waveguides. The breakup of symmetry between active and lossy parts can happen by unstable fluctuations and results in blowup of soliton or a breather state is formed. The fluctuations in low frequency soliton separate its two components in space and this also leads to the blowup or breathing.

I. V. Barashenkov et al. [28] demostate the formation of Breathers in PT -symmetric optical couplers.they demonstrated that parity-time- (PT -) symmetric coupled optical waveguides with gain and loss support localized oscillatory structures similar to the breathers. The power of breather soliton oscillates periodically, switching back and forth between the waveguides and loss and gain are compensated. The breathers are prevalent in soliton collisions.they showed that brether solitons are stable by solving coupled nonlinear Schrodinger equations.

Xianling Shi, Boris A. Malomed Fangwei Ye,and Xianfeng Chen [29] investigated Symmetric and asymmetric solitons in a nonlocal nonlinear coupler. They study effects of nonlocality of cubic nonlinearity on the stability and symmetry-breaking bifurcation (SBB) of solitons in presence of nonlocal nonlinearity. Two competitive effects are present- the coupling length and correlation radius of the nonlocality. They found that, the SBB changes from subcritical into supercritical by increase of the correlation radius. This would make all the asymmetric solitons stable.they found that the nonlocality has little influence on the stability of antisymmetric solitons.

P. L. Chu, B.A. Malomed, G. D. Peng, and I.M. Skinner [30] studied the Soliton dynamics in periodically modulated directional couplers. They use variational approach to study the effects. The influence on switching of direct and parametric resonances between the period of the energy oscillation within the coupler and the periodic modulation is considered.it has been found that effect of modulation splits the stationary symmetric soliton into a pair of asymmetric ones. They examine the effect of a small periodic perturbation on a soliton input into one arm of a directional coupler .they found that as soliton approaches the threshold energy for switching ,the size of the perturbation required to cause chaotic coupling between the arms reduces, until exactly at threshold that is P_0 =1 , any perturbation causes chaos. The perturbation leads to internal oscillations in system.

Arthur R. McGurn [31] studied localized modes and waveguide couplers in photonic crystal circuits.he proposed circuits design which include waveguide channels containing dielectric barriers, channel bends, or junctions with other waveguides.Photonic circuits waveguide channels of both linear and nonlinear dielectric materials are considered. The waveguide coupler in which energy to be transfered from one waveguide channel to another through weak interchannel interactions is proposed.

Hideaki Takashima et al.[32] demonstrated Efficient optical coupling into a single plasmonic nanostructure using a fiber-coupled microspherical cavity. they propose a tapered-fiber-coupled microspherical cavity system combining an Au-coated probeto get complete coupling between propagating light (PL) and a single localized-surface-plasmon (LSP) nanostructure.the system has precise nature to adjust fiber-cavity coupling rate and the cavity-plasmon coupling rate.they successfully demonstrated 93% coupling into the LSP antenna with an effective area of a 58 nm circle.

Abdel-Baset ,M. A. Ibrahim, B. A. Umarov, and M. R. B. Wahiddin [33] demonstrated squeezing in the Kerr nonlinear coupler via phase-space representation.they investigate quantum-statistical properties of light propagating in a coupler with third order nonlinearity.they showed numerically the possibility to generate quadrature-squeezed states . they calculate quadrature variances of single modes to determine the possibility ofsqueezing for light propagating in a NLDC.

Yongyao Li, Jingfeng Liu, Wei Pang, and Boris A. Malomed [34] in their paper investigated symmetry breaking in dipolar matter-wave solitons in dual-core couplers. They use system composed of a dipolar Bose-Einstein condensate trapped in a dual-core system with dipole-dipole interactions (DDIs) and hopping between the cores.two scenarios of a matter-wave coupler are studied: weakly and strongly coupled. They found SSB of the supercritical and subcritical types in weakly and strongly coupled respectively.the stability regions are discovered .The intercore dipole-dipole interactions are also studied.

Danny O’Shea et al.[35] in their paper designed a optical fiber coupler which is controlled by single atom. The design consists of whispering-gallery-mode bottle microresonator which is coupled to a single atom and interfaced by two tapered fiber couplers. They investigate the switching efficiency of our system that is probability of optical switch to redirects light into desired input.they also demonstrate that proposed switch exhibits a photon-number-dependent routing capability.

Daria A. Smirnova et al.[36] in their paper demonstrate Nonlinear switching with a graphene coupler. They studied nonlinear propagation of electromagnetic waves in two closely spaced graphene layers numerically and analytically and proved that double-layer graphene waveguide can efficiently operate as an optical coupler. They studied effects induced by nonlinearity and predicts that interlayer coupling which is power dependent can provide optical beam control at realistic input levels and also studied symmetry breaking.

J. M. Fang and M. J. Potasek [37] investigated optical switching in the presence of two-photon absorption for a nonlinear directional coupler. They considered a large nonlinear index of refraction accompanied a significant amount of two photon absorption (TPA), and TPA tends to limit all optical switching. They proved that switching is possible in case of two-photon absorption. It has been further demonstrated that output pulses can be controlled by relative phase between input pulses and the output pulses retain their shape.

J.W.M. Menezes , W. B. de Fraga , M.G. da Silva [38] has done the numerical analysis in triangular and planar three-core nonlinear optical fiber couplers operating logical gates. They have shown by solving coupled nonlinear Schrödinger equations (NLSEs), that logic gates AND, OR and NXOR can be constructed from a triangular nonlinear directional coupler. The planar TNLDC produced logical gates AND, NAND, OR, and XOR.They use two models,in first model they have 3 core equilateral-triangle arrangement and a control signal is applied at first core .The second model uses planer symmetrical structure with all cores in parallel equidistant arrangement and control signal is applied at first core .by studying cross channel and direct channel they calculated extinction ration of these devices. To compare the logic gates performance they used figure of merit of logic gates.

Y Zhu, V A Handerek, A J Rogers and J Kanka [39] in their paper analyzed 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 analyzed 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 solitonic modelocking 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.

Masaaki imai, shinya and narihiro eta [40] has done investigation on all optical switching of a nonlinear fiber-optic grating coupler utilizing cross-phase modulation of intense pump pulse at 1.55 um. They used a mode locked EDFA laser Kerr nonlinearily in the grating region of the FGC due to cross-phase modulation. They showed in their analysis that 3dB of extinction ratio is obtained for a pump power of approximately 3kW. The power can he further reduced if a phaseshift grating coupler in which a Π/2 phase-shift grating is formed at half coupling length.

Xiujun Hea, Kang Xiea, Huajun Yanga [41] analyzed Gain-induced soliton switching in fiber nonlinear directional coupler. They found influence of elements on switching characteristics by providing gain in fiber core 1 and core 2 . they found numerically that switching efficiencies were improved by controlling gain of core 1 and proved that by controlling gain of cores we can obtain different output coupling ratio .they change gain by changing pump powers of optical fiber amplifiers.they made a variable coupler in which output coupling ratio can be changeable.

Xiujun Hea, Kang Xiea, Huajun Yanga [42] in their paper studied the Optical solitons switching in asymmetric dual-core nonlinear fiber couplers. They found that switching efficiencies can change by changing signs of dispersion of two fibers.The result is that dispersion values of two fibers have opposite signs have higher efficiencies than those when they have same signs. They also found that switch efficiencies become much higher if the dispersion value of one core is decreased in case of dispersion values of same sign in both fiber cores. They further showed switch threshold power becomes lower than the one with the same sign if the nonlinearity coefficient of two fibers is opposite. So they found asymmetric coupler having good switching efficiency than symmetric coupler.

Ajit Kumar , Amarendra K. Sarma [43] in their paper has done variational analysis of soliton switching in a Kerr coupler with coupling constant dispersion caused by caused by intermodal dispersion between the symmetric and the anti-symmetric modes of the coupler.the calculated the switching characteristics and they found it is same for pulse widths of 10 fs to 100fs.te dependence of switching energy on coupling constant is also studied. The pulse variations and variations in amplitude are calculated and found agreed with numerical results.

M.G. da Silva, A.S.B. Sombra [44] investigated All-optical soliton switching in three-core nonlinear fiber couplers. They analyzed propagation and the switching of solitons in a three-core nonlinear fiber.They used variational and lagrangian method of analysis. They solve the coupled nonlinear schrodinger equations and the results are compared with numerical results.they showed the existence of eigenstates where there is no coupling between fibers is observed. Lgrangian analysis results are proved better and soliton switching in nonlinear fiber couplers provides possibilities for achieving, high efficiency in ultrafast all-optical signal processing, especially for optical switches and optical transistors.

J.W.M. Menezes , W.B. de Fraga , G.F. Guimara˜es , A.C. Ferreira , H.H.B. Rocha ,M.G. da Silva , A.S.B. Sombra [45] investigated Optical switches and all-fiber logical devices based on triangular and planar three-core nonlinear optical fiber couplers. They analyzed switching process in a triangular (T) and planar (P1 and P2) symmetric three-core nonlinear fiber coupler.they have shown from CNLSE that AND, NAND, OR, NOR, XOR, NXOR and NOT logic gates can be constructed. A triangular (TNLDC-T) is symmetrical structure and consists of three cores in an equilateral-triangle arrangement and use a control signal in input of first core.The configurations consists a planar symmetrical structure with three cores in a parallel equidistant arrangement. The control signal is applied at different input positions.

P. A. Buah, B. M. A. Rahman and K. T. V. Grattan [46] investigated Numerical Study of Soliton Switching in Active Three-Core Nonlinear Fiber Couplers. They use finiteelement-based beam propagation algorithm in their analysis. The switching of solitons in coupler in presence of gain is presented. The Linear gain is found to lead to sharper transmittance characteristics and it results in lowering of threshold power of switching. It also results in increase in the power transfer between the input and center core for a nearest-neighbor core. The finite gain bandwidth leads to deterioration of switching characteristics same as in case of two core coupler.

A Govindarajia, A. Mahalingamb, A. Uthayakumara [47] investigated Femtosecond pulse switching in a fiber coupler in presence third order dispersion and self-steepening effects.They use split step fourier method to solve coupled nonlinear Schrödinger equations .they observed that switching characteristics does not change except changing pulse shapes to super Gaussian. They found that third order dispersion and self steepening deteriorates the switching characteristics at higher input powers.

Amarendra K. Sarma [48] has done analysis of Vector soliton switching in a fiber nonlinear directional coupler. He has done in his paper numerical study of soliton switching in a high as well as low birefringent nonlinear coupler. He showed that we can get nearly 100% transmission with excellent switching characteristics controlling the polarization angle . he found the soliton remain more stable in high birefringent coupler.he found that even before threshold power of switching a coupler can be used as a switch at 50:50 power ratio by properly choosing polarization angles.

A.Govindaraji , A.Mahalingam , A.Uthayakumar [51] investigated Dark soliton switching in nonlinear fiber couplers with gain.they did numerical simulations for switching dynamics of dark solitons in fiber coupler. The higher order nonlinear effects are also considered. Gain is provided in both of fiber cores .the effect of second order coupling coefficient is also studied . They found that providing gain the switching threshold decreases in cross channel whereas in bar channel it acts opposite way. The effect of second order coupling coefficient is not so much as compared to bright solitons.

Xiujun He [52] in the paper studied Phase-induced switching in fiber nonlinear directional coupler.A numerical study is presented .the maximum output coupling is presented by controlling phase changes of control pulse by various parameters. they found input powers ratio, coupled coefficient and soliton width have high impact in soliton switching and that these effects may lead to useful soliton switching provided phase changes are controlled efficiently. This leads to variable coupler having coupling ratio control by phase changes.they also study impact of input soliton width and input power on switching dynamics of fiber coupler.

H. Yokota , M. Kobayashi , H. Mineo , N. Kagawa , H. Kanbe , Y. Sasaki [53] in their paper demonstrated an all-optical switching operation using an optical fiber grating coupler which is a fused optical fiber coupler with a tapered region in which refractive index-modulated gratings are written. The light consists of various wavelengths are launched in coupler. The wavelengths which satisfy grating condition move to desired output port and other wavelengths to second output port. It can be used as all optical switch .they calculated switching efficiency which was 7%. They also found that bragg wavelength shift is caused by third order nonlinear effect and photothermal effect.

M.G. da Silva et al. [54] have done analysis of optical crosstalk in a periodically inhomogeneous nonlinear dispersion directional fiber coupler they have done numerical analysis of the propagation and the switching of fundamental solitons

in a two-core nonlinear fiber coupler which is manufactured with periodically modulated dispersion fiber. They considered different amplitude and frequency modulations of periodically modulated dispersion fiber. For low to high pump energies the critical energy, the compression factor, the crosstalk (Xtalk) and extinction ratio (Xratio) levels are studied in case of first order solitons . They observed that at low modulation frequencies pump power results in an increase of the critical energy and decrease of the transmission efficiency. at high pump powers the transmission is less efficient in case of higher modulation frequencies. The pulses after switching have broader shape for low frequency and high amplitude of modulation. They observed that with increase of pump power the Xtalk level decreases. At higher frequencies the increase of the amplitude modulation results in the Xtalk to reach a minimum as a function of pump power. They calculate all effects of

periodically modulated dispersion profile on switching dynamics of NLDC.

Basanti Mandal, A. Roy Chowdhury [55] investigated effect of Raman scattering and switching of soliton pulse in fused fiber coupler. Same type of dispersion management is used for both the cores. They studied switching dynamics by moment method and effect of variations of the different parameters of the Gaussian pulse, such as chirp, frequency, energy etc.they also discussed switching phenomena due to the coupling in fused fiber coupler. They showed that by launching a pulse in one core of the coupler can generate pulses in both the fiber cores , but the strength of coupling changes significantly when strength of intrapulse Raman scattering is changed .

Soumendu Jana, Swapan Konar, and Manoj Mishra [56] investigated Soliton Switching in Fiber Coupler with Periodically Modulated Dispersion, Coupling Constant Dispersion and Cubic Quintic Nonlinearity both analytically and numerically. They found that quintic nonlinearity has significant effect on switching dynamics. They successfully derived the expressions for transmission coefficient, cross talk and extinction ratio in the context of both quintic nonlinearity and periodically modulated dispersion.

Mehdi Tajaldini , Mohd Zubir MatJafri [57] in their paper proposed an ultra-compact multimode interference coupler as an optimum all-optical switch based on nonlinear modal propagation analysis. They used modal propagation analysis (MPA) to study optical switch based on a small-dimension multimode interference (MMI) coupler at the threshold of the nonlinear regime. They found that modal characterization indicates change such as conversion of sinusoidal profile to Gaussian profile and appearance of sifferent amplitudes and phases for guided modes. The proposed switch is optimized via output width and switching efficiency is analyzed.

Prasanta Mandal, Swati Midda [58] proposed an all optical method of developing OR and NAND logic system based on nonlinear optical fiber couplers. They constructed NAND and OR logic operation by considering three optical fibers coupled together. the input powers are given in fiber 1 and fiber 3 only, no input power is given in fiber 2.by changing the input light intensities in fiber cores the coupling length changes and it results in logic gate operations. In their system,it uses the optical fiber for guiding the light and organizing the logic operation, only a mW level of optical power or less than that is enough for supporting the logic operation which is much better as compared to Mach–Zehnder modulator in which the power consumption to implement logic functions is quite high. they implemented NAND and OR logic function by this coupler design .

Qiliang Li, Hongliang Yuan [59] proposed all-optical logic gates based on cross-phase modulation in an asymmetric coupler. They examine two-input OR and XOR gates and a new logical operation based on an asymmetric nonlinear directional coupler .this operation can be used in processing of signals in all-optical systems. In their design they inserted a pulse into the nonlinear directional coupler and adding a pump light via wavelength division multiplex in order to take advantage of Kerr effect and produce the cross-phase modulation. They showed that AND and XOR gates are realized by changing pump power.

M. Liu and P. Shum [60] in their paper analyzed Effects of Intermodal Dispersion on Short Pulse Propagation in an Active Nonlinear Two-Core Fiber Coupler. They observe interaction between intermodal dispersion and gain bandwidth .they have done numerical analysis of system.They found that pulse breakup effect caused by intermodal dispersion can be corrected by finte bandwidth of linear gain.

Jorge R. Costa, Carlos R. Paiva and Afonso M. Barbosa [61] investigated numerical Study of Passive Gain Equalization with Twin-Core Fiber Coupler Amplifiers for WDM Systems. They analyzed propagation of WDM pulses in a coupler and a chain of couplers and effect of intermodal dispersion is analyzed. They predicted that chain of twin-core fiber coupler amplifiers is provide a lower final power span between WDM channels than conventional EDFAs. The coupler also has benefit of having regeneration capabilities and able to recover accidental power loses. They do not include amplifies stimulated emission noise as it has bidirectional nature and split step is forward propagating algorithm

Youfa Wang and Wenfeng Wang [62] in their paper studied the Ultrafast Pulse Coupling Dynamics Considering Retarded Nonlinear Response and Self-Steepening Effects. They have done analysis considering higher-order dispersion, retarded nonlinear response, and self-steepening terms in coupled Schrödinger equations. Their results showed the effect of the retarded nonlinear response and self-steepening effect on the switching characteristics in a nonlinear directional coupler. The results dependent on input pulse width,pulse power and product term of dispersion and coupling coefficient .they found that retarded nonlinear response improves switching dynamics of fiber coupler**.** They found that we can ignore effects of self steepening and retarded nonlinear response if normalized amplitude is less than 0.5.

A.G. Coelho, Jr., M. B. C. Costa, A. C. Ferreira, M. G. da Silva, M. L. Lyra, and A. S. B. Sombra [61] in their paper has done the Realization of All-Optical Logic Gates in a Triangular triple-Core Photonic Crystal Fiber.They proposed an all optical logoc gate in which two ultrashort pulses are used of 100 fs. The modulation used is amplitude shift keying with binary amplitude modulation. They consider effects of of self-phase modulation (SPM), cross-phase modulation(XPM), self-steepening, and intrapulse Raman scattering (IRS) in a lossless configuration. They found that ther is possibility to get logic gates realization by controlling phase difference between input pulses.

CHAPTER 4

Soliton Switching in Nonlinear Fiber Directional Coupler in Presence of Random Dispersion

4.1 Introduction

The nonlinear directional coupler has been center of research since it has number of technological applications. One of main attractive feature is switching at high bit rates in an all optical systems [58]. 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. The solitons pulses are used to study switching characteristics are used because of their higher switching efficiency and results are more authentic one. Also soliton communication systems are going to be available commercially as lot of research is going on due to its attractive feature of perfect balance between dispersion and nonlinearities to maintain constant shape. The effects of intermodal dispersion higher order nonlinear effects has been studied in fiber coupler. In practical systems, we face random dispersion due to following reasons

(1) The fluctuations occurred in core cladding diameter
(2) The variation in doping concentration along length of fiber.
(3) Environmental factors like thermal stress.

So effects of random dispersions play a key role in maintaining quality of transmission. To best of our knowledge the switching characteristics of nonlinear directional fiber coupler in presence of random dispersion has not been reported till date. We investigated the random dispersion impact on switching dynamics of nonlinear directional fiber coupler. To make our study in total practical conditions , we include all other higher order nonlinear effects namely quintic nonlinearity, Intrapulse Raman scattering and self steepening. We also include third order dispersion in our study. The intermodal dispersion is also taken into account we introduce random dispersion in a practical fiber coupler .Our goal is to find the tolerable random dispersion to which if our fiber coupler is subjected to still perform as an efficient switch.

4.2 Methodology: Split Step Fourier Method

We employed Split Step Fourier method to analyse the performance of nonlinear directional coupler. Split step Fourier method is a numerical method used to solve Partial differential equations. In numerical analysis of Coupled Nonlinear Schrodinger equations, it could be used effectively. This method computes the solution in small steps .So the distance is propagated by applying SSFM at small step size. It solves the nonlinear terms in time domain and linear parts in frequency domain. So fourier transforms are used to do solve in frequency domain. It is very effective to study light pulse propagation in optical fibers where linear and nonlinear mechanisms make it difficult to find general analytic solutions

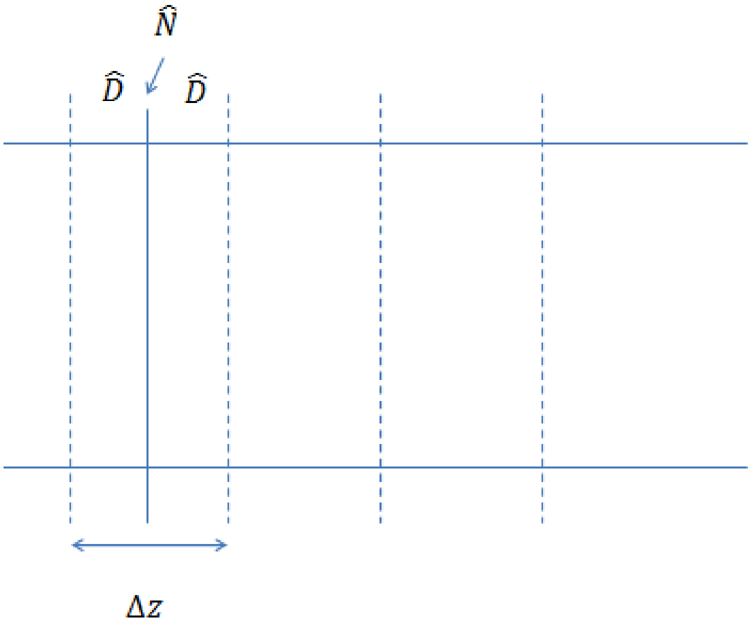


Fig.4.1. Split Step Fourier Method

First linear part that is dispersion effect is applied at distance half of Δz ,then nonlinearity terms effect is included for step size Δz at distance half of Δz. After this, again dispersion terms effect is applied for rest half of Δz. In this way pulse propagation is analyzed by propagating small distances equal to step size to cover whole distance.

The coupled nonlinear Schrodinger equations are

$$i\left(\frac{\partial A_1}{\partial Z}+K_1\frac{\partial A_2}{\partial T}\right)+\frac{P(r)}{2}\frac{\partial^2 A_1}{\partial T^2}-i\frac{\beta_3}{6}\frac{\partial^3 A_1}{\partial T^3}+\gamma|A_1|^2A_1+\gamma_2|A_1|^4A_1+\frac{i}{\omega_0}\frac{\partial}{\partial T}(|A_1|^2A_1)$$
$$-T_R A_1\frac{\partial|A_1|^2}{\partial T}=-K_0A_2$$

$$i\left(\frac{\partial A_2}{\partial Z}+K_1\frac{\partial A_1}{\partial T}\right)+\frac{P(r)}{2}\frac{\partial^2 A_2}{\partial T^2}-i\frac{\beta_3}{6}\frac{\partial^3 A_2}{\partial T^3}+\gamma|A_2|^2A_2+\gamma_2|A_2|^4A_2+\frac{i}{\omega_0}\frac{\partial}{\partial T}(|A_2|^2A_2)$$
$$-T_RA_2\frac{\partial|A_2|^2}{\partial T}=-K_0A_1$$

To apply split step Fourier method, we first split our equations into linear and nonlinear terms, the linear terms (Dispersion terms) are written as

$$\frac{\partial A_1}{\partial Z}=i\frac{P(r)}{2}\frac{\partial^2 A_1}{\partial T^2}+\frac{\beta_3}{6}\frac{\partial^3 A_1}{\partial T^3}-K_1\frac{\partial A_2}{\partial T}+iK_0A_2$$

$$\frac{\partial A_2}{\partial Z}=i\frac{P(r)}{2}\frac{\partial^2 A_2}{\partial T^2}+\frac{\beta_3}{6}\frac{\partial^3 A_2}{\partial T^3}-K_1\frac{\partial A_1}{\partial T}+iK_0A_1$$

The nonlinear terms are obtained as

$$\frac{\partial A_1}{\partial Z}=i\left(\gamma|A_1|^2A_1+\gamma_2|A_1|^4A_1-T_RA_1\frac{\partial|A_1|^2}{\partial T}\right)-\frac{1}{\omega_0}\frac{\partial}{\partial T}(|A_1|^2A_1)$$

$$\frac{\partial A_2}{\partial Z}=i\left(\gamma|A_2|^2A_2+\gamma_2|A_2|^4A_2-T_RA_2\frac{\partial|A_2|^2}{\partial T}\right)-\frac{1}{\omega_0}\frac{\partial}{\partial T}(|A_2|^2A_2)$$

The nonlinear terms are solved in time domain. To solve linear terms we have to take Fourier transform and apply the operations. The solution of equations is of form

$$\mathrm{A}(z+h/2,\omega)=\exp(gh/2)\ \mathrm{x}\ [\mathrm{A}(z,\omega)+(ih/2)C\,A_2(z,\omega)]$$

Then we take inverse Fourier transform to take it back in time domain. The nonlinear terms are applied in time domain. After that again we take Fourier transform and apply linear terms for rest of distance. In this way we propagate the length of coupler and observed the output signal in desired output port in terms of transmission factor which is given as

$$\mathrm{T} = \frac{\int_{-\infty}^{\infty} |\mathrm{u}(\xi, \mathrm{L})|^{2}}{\int_{-\infty}^{\infty} |\mathrm{u}(\xi, \mathrm{L})|^{2} + \int_{-\infty}^{\infty} |\mathrm{v}(\xi, \mathrm{L})|^{2}}$$

4.3 Results and Discussion

The following parameters are taken in our study

$\lambda = 1.55\mu m$ (operating wavelength)

$\beta_2 = -20\ ps^2/km$ (GVD coefficient)

$\gamma = 3\ W^{-1}/km$ (Kerr nonlinearity parameter)

$k_0 = 0.3$ (linear coupling coefficient)

$\beta_3 = 0.12\ ps^3/km$ (third order dispersion coefficient)

$\delta = -0.1$, (first-order coupling constant dispersion coefficient)

$T_R = 5$ fs (Intrapulse Raman scattering parameter)

$\frac{1}{\omega_0} = 8$ fs (Self-steepening parameter)

The length of nonlinear directional coupler is taken equal to half beat Length $(L_b = \frac{\Pi}{2k_0})$.

The initial conditions considered to study NLDC switching characteristics

$$u = A \sec h(At)$$

$$v = 0$$

The input to first fiber core is fundamental soliton pulse and there is no signal at input of second core .We analyse the transmission factor as function of input power of soliton to study switching characteristics of coupler.

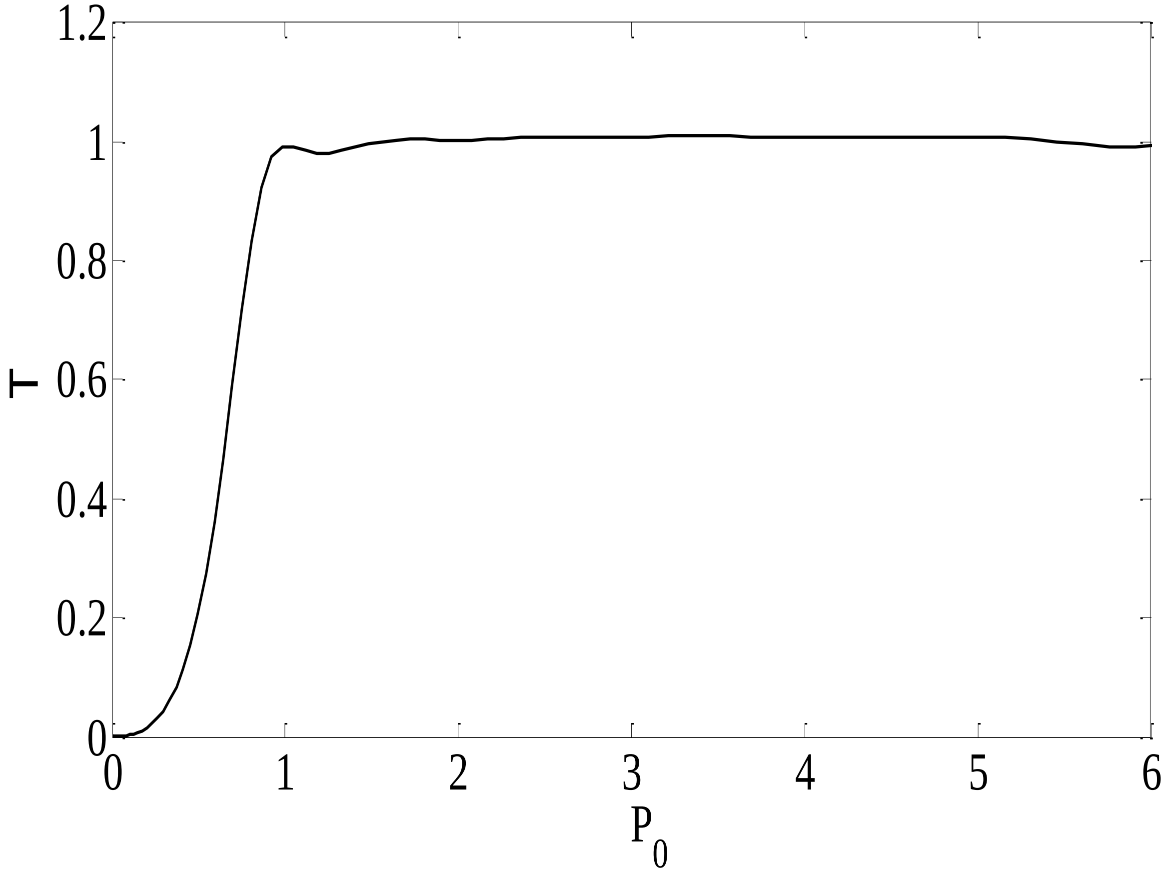


Fig.4.2. Switching characteristics of two core nonlinear directional fiber coupler as function of input Power P_0 in Kerr nonlinear medium.

Fig.4.2. shows the switching characteristics of NLDC in Kerr nonlinear medium. We found that switching occurs when input power is equal to 1mw. If we consider higher order nonlinearity that is quintic nonlinearity we get very interesting variation in switching dynamics .Fig.4.3. Shows switching dynamics after introduction of quintic nonlinearity .we take sign of quintic nonlinearity as negative because in our study we consider defocusing type of quintic nonlinearity. We take different values of quintic nonlinearity and study behaviour of switching dynamics .we found that as the quintic nonlinearity value increases the transmission factor value decreases which means switching could not take place as transfer of power is not completely back into input core 1 and some power is transfer into core 2 also. We conclude that quintic nonlinearity has detrimental effect on switching characteristics of nonlinear fiber directional coupler. we found that for $\gamma_2 = -0.01$, the switching characteristics remains same as in kerr nonlinear medium. So we take $\gamma_2 = -0.01$ for further analysis of NLDC.

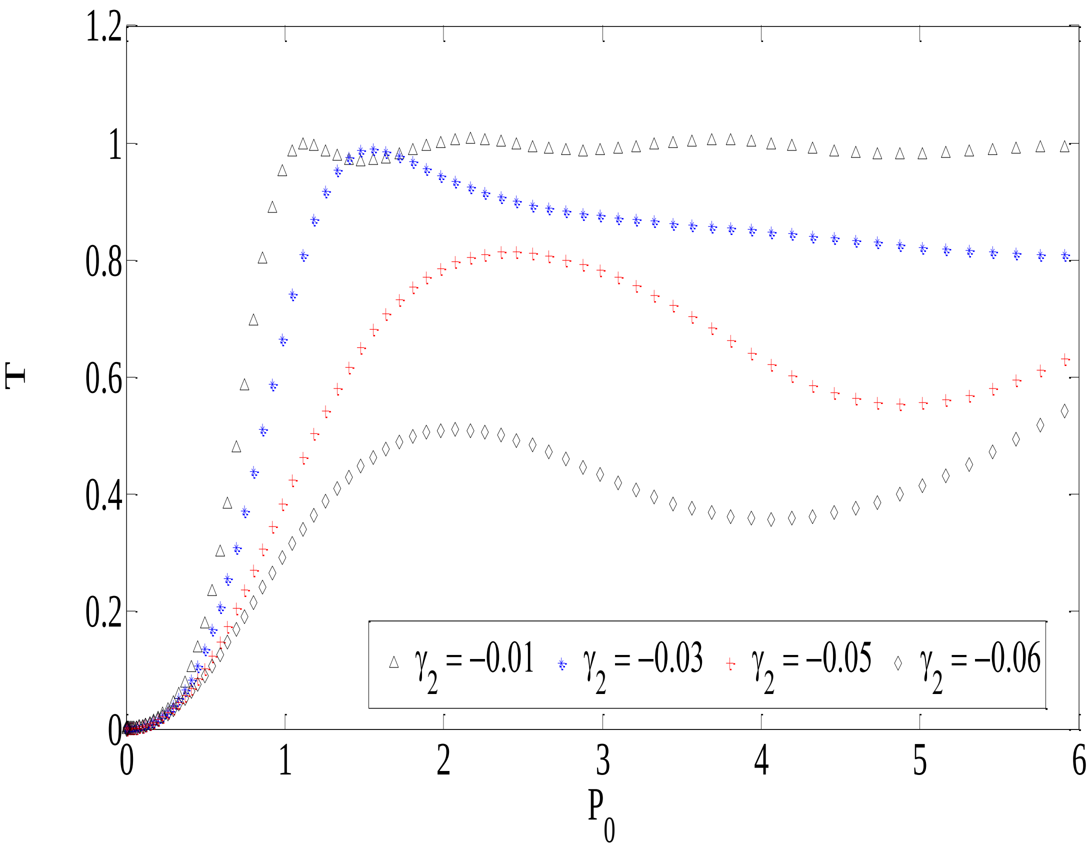


Fig.4.3. Switching characteristics of two core nonlinear directional fiber coupler as function of input Power P_0 in Cubic –Quintic nonlinear medium.

Fig.4.4. shows effect of third order dispersion on switching characteristics of nonlinear directional coupler. We know that in presence of third order dispersion as pulse moves its shape gets change because of ripples appears at starting or trailing edges of pulse and energy decreases. We apply third order dispersion in presence of cubic–quintic nonlinear medium intermodal dispersion. We found that as the value of third order dispersion increases it results in fluctuations in switching dynamics of nonlinear directional coupler. As we varied the value of factor β_3 from 0.12 ps^3 /km to 1 ps^3 /km, the switching characteristics deteriorate as shown in fig.4.4. The value of transmission factor does not remain constant after switching and it distort the sharp switching characteristics obtained in absence of third order dispersion. We found that for β_3 =0.12 ps^3 /km, the switching characteristics remain sharp and as desired by designer of nonlinear fiber directional coupler.

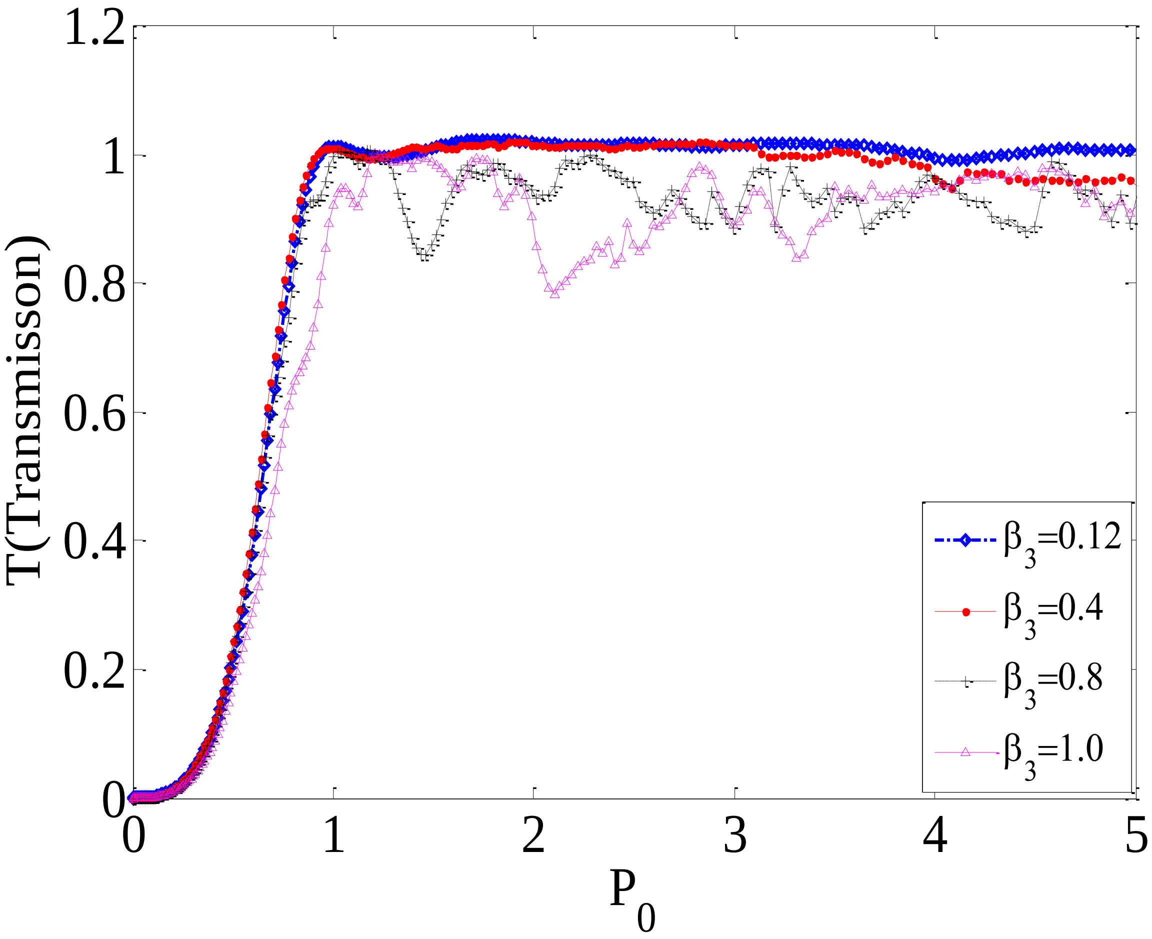


Fig.4.4. Switching characteristics of two core nonlinear directional fiber coupler as function of input Power P_0 with $\gamma_2 = -0.01$ for different values of β_3.

We analyze the switching characteristics in presence of random dispersion .we introduce random dispersion in group velocity dispersion .we calculate value of transmission factor which is ratio of output power in desired port and total power input in fiber coupler.Fig.4.5 shows the switching characteristics in presence of 5 percent random dispersion. We get randomness in switching curves but still we get very faithful switching in presence of 5 percent random dispersion.

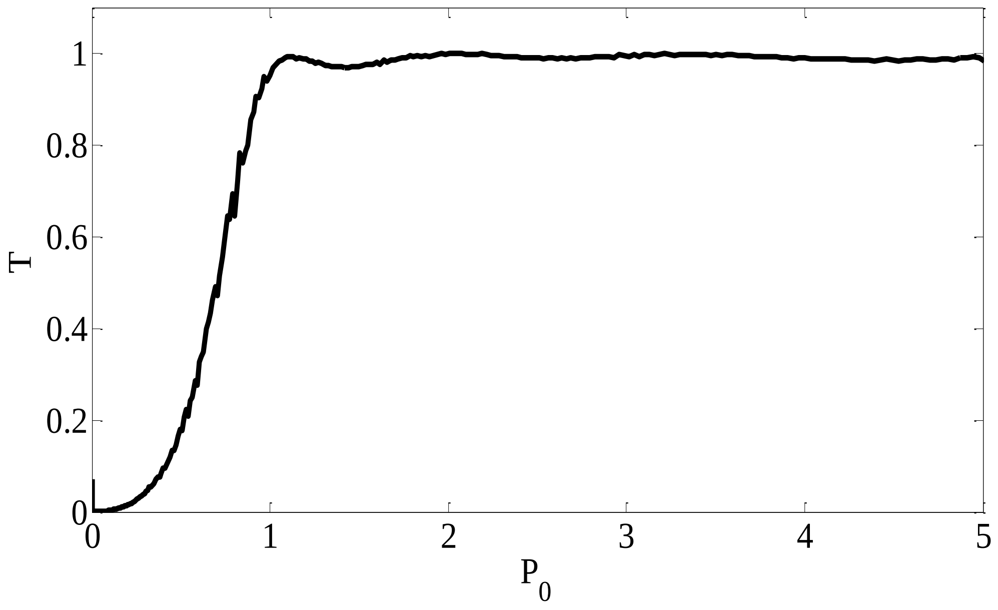


Fig.4.5. Switching characteristics of two core nonlinear directional fiber coupler as function of input Power P_0 in presence of 5 percent random dispersion.

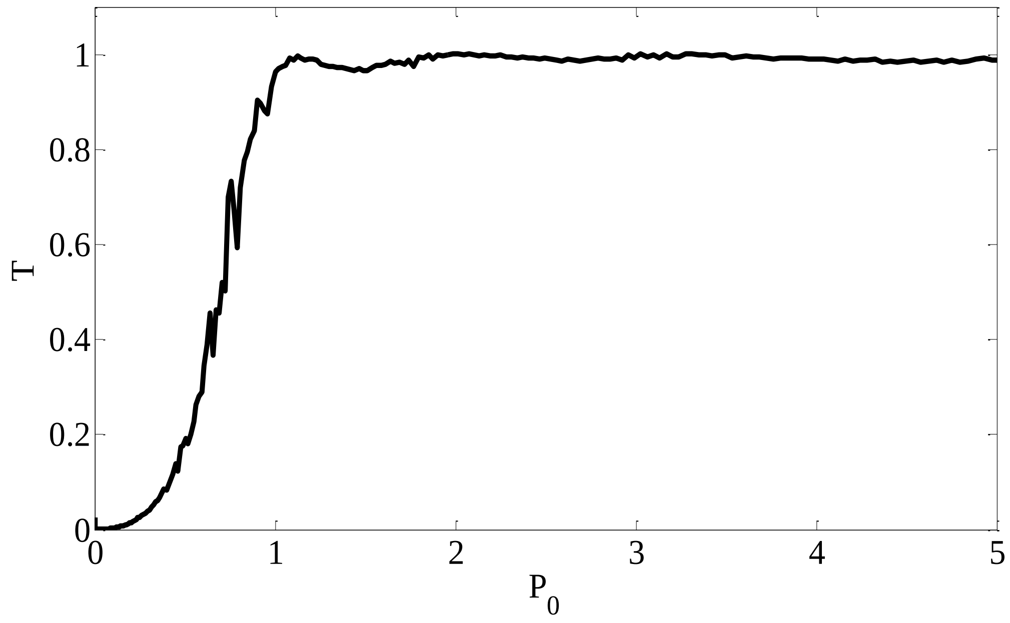


Fig.4.6. Switching characteristics of two core nonlinear directional fiber coupler as function of input Power P_0 in presence of 10 percent random dispersion.

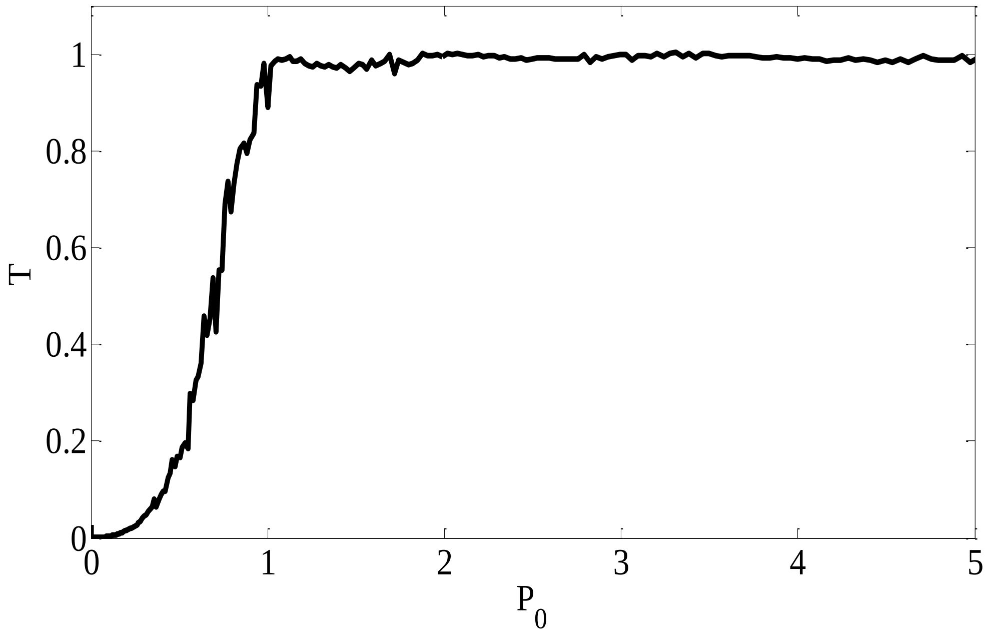


Fig.4.7. Switching characteristics of two core nonlinear directional fiber coupler as function of input Power P_0 in presence of 15 percent random dispersion.

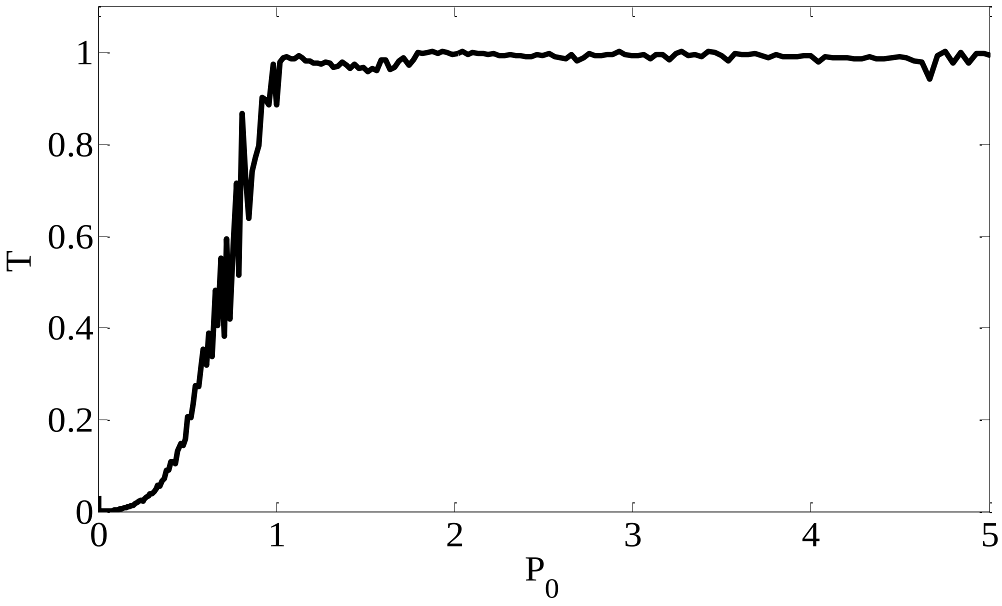


Fig.4.8. Switching characteristics of two core nonlinear directional fiber coupler as function of input Power P_0 in presence of 20 percent random dispersion

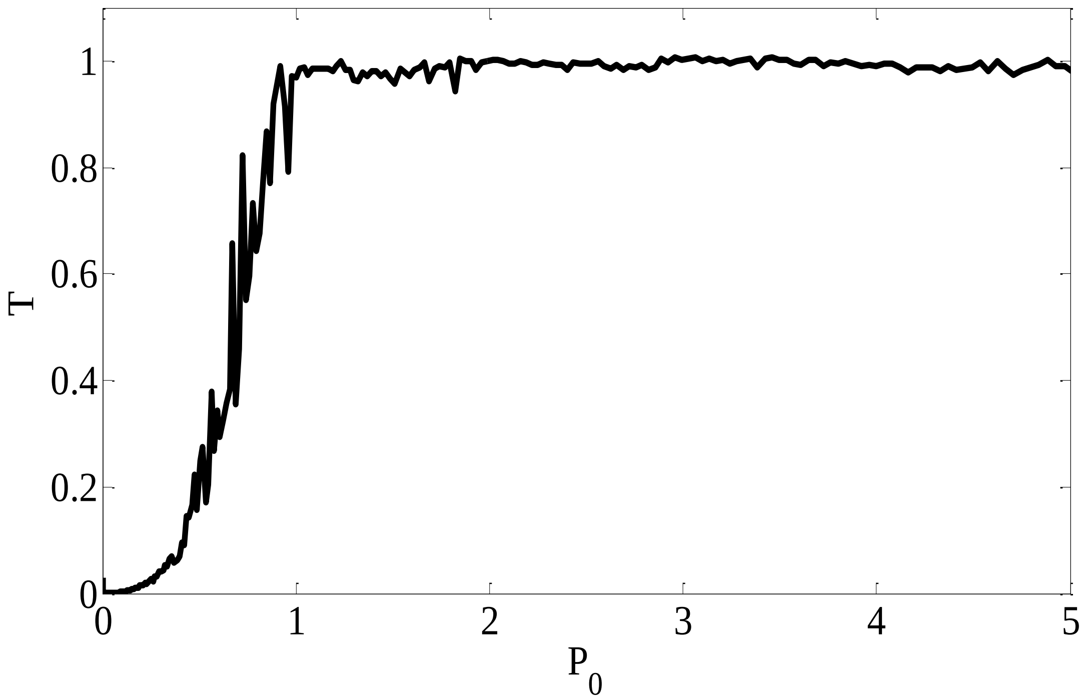


Fig.4.9. Switching characteristics of two core nonlinear directional fiber coupler as function of input Power P_0 in presence of 30 percent random dispersion.

Fig.4.6. shows the switching dynamics of nonlinear directional coupler in presence of 10 percent random dispersion. We found that as we increase the value of random dispersion from 5 percent to 10 percent, it results in changes in switching characteristics curve of fiber coupler. We found that before switching threshold power, we get increase in randomness as compared to 5 percent random dispersion results. Fig.4.7. shows the switching characteristics of nonlinear directional coupler in presence of 15 percent random dispersion. We found increase in random dispersion to 15 percent create more chaos in switching behaviour of coupler. Fig.4.8. shows the switching curve of nonlinear directional coupler in presence of 20 percent random dispersion and Fig.4.9. shows the switching curve in presence of 30 percent random dispersion. We found that increase in random dispersion has deteriorating effect on switching characteristics of nonlinear directional fiber coupler .we found that 5 percent random dispersion is permissible in non linear fiber coupler switching performance.

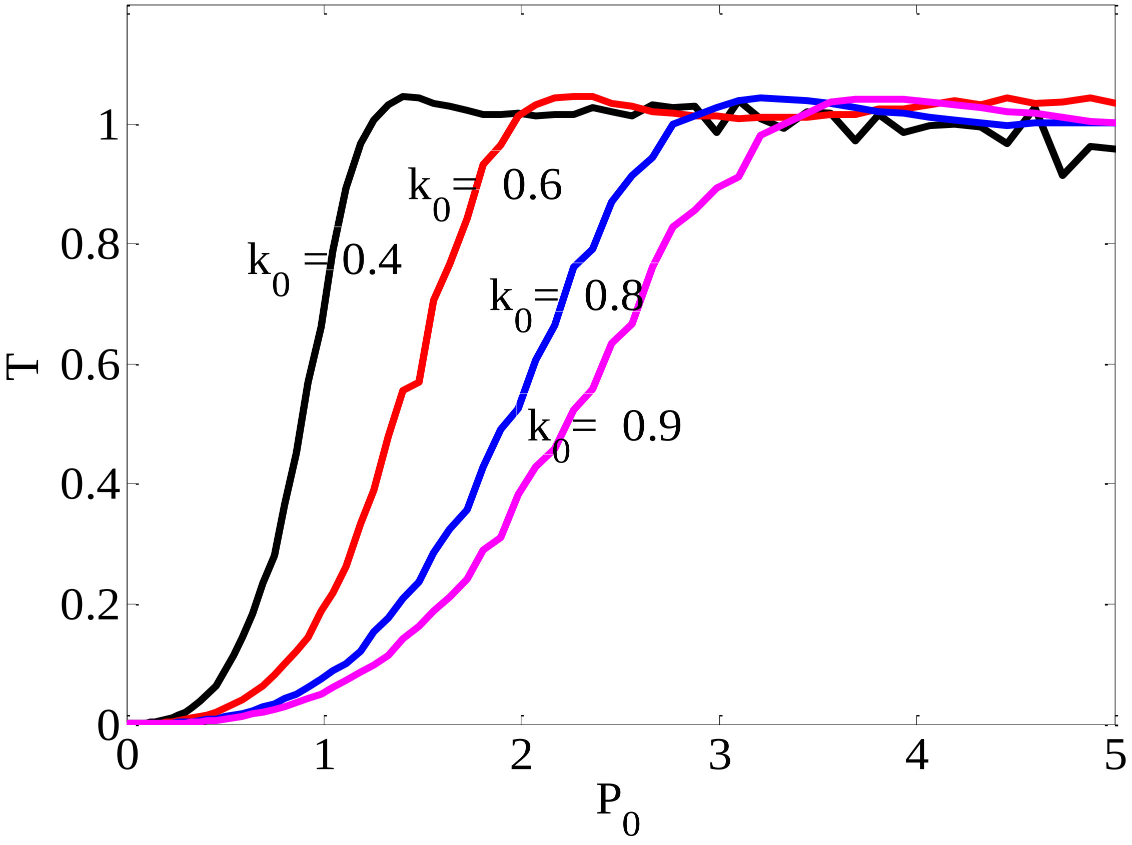
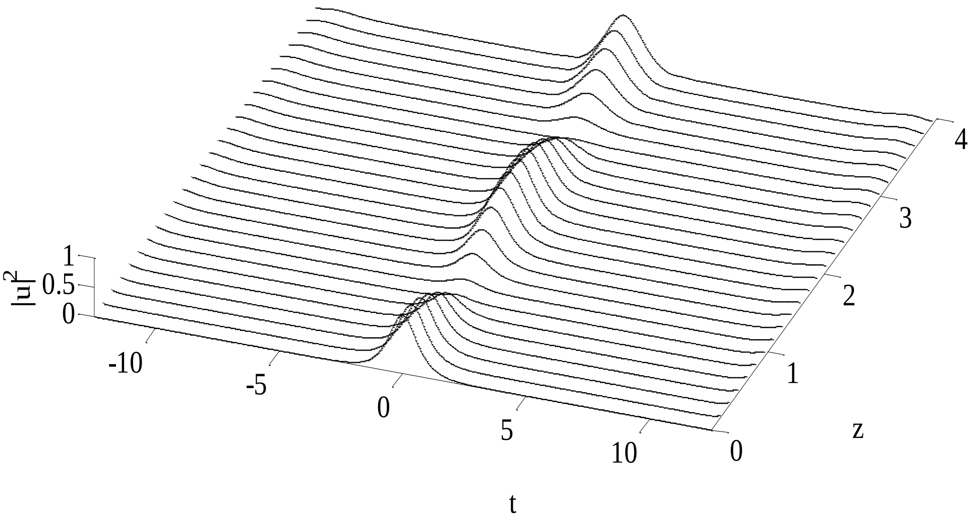
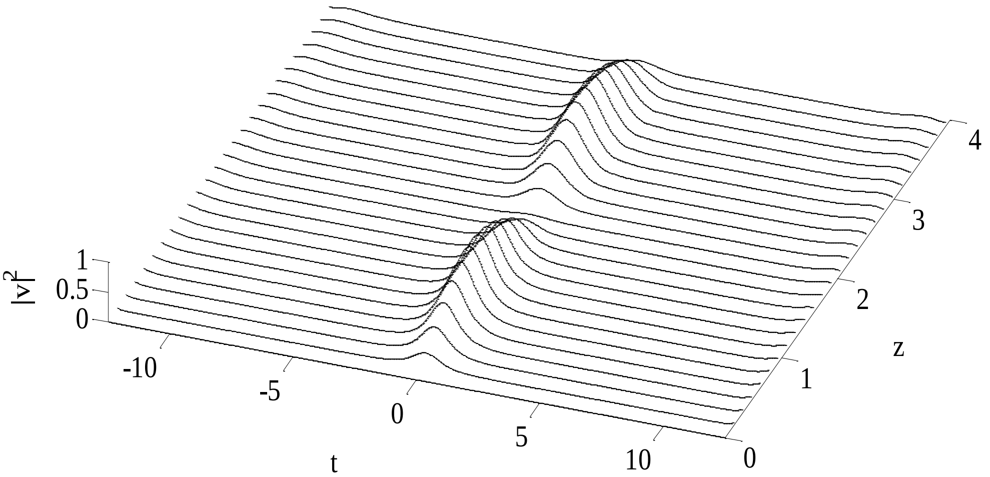


Fig.4.10. Switching characteristics of two core nonlinear directional fiber coupler as function of input Power P_0 in presence of 5 percent random dispersion with different values of coupling coefficient.

Fig.4.10. shows the switching dynamics of NLDC in cubic quintic nonlinear medium with quintic nonlinearity equal to -0.01 which is of defocusing nature and random dispersion equal to 5 percent. The higher order effects third order dispersion, intermodal dispersion, intrapulse Raman scattering and self steepening effects are also included. From the figure we found that with increase in linear coupling coefficient results in increase in switching threshold value. When $k_{0=}$ 0.3, we get switching at P_0=1 mw in cubic – quintic medium .when $k_{0=}$ 0.6, the switching threshold increases to value P_0= 2 mw. Further increase in linear coupling coefficient results in increase in switching threshold power we can control the threshold level at which switching take place at also power level for 50:50 splitting ratio.



(a)



(b)

Fig.4.11. Evolution of solitons *u and v* along the propagation length of the nonlinear directional coupler (NLDC) in cubic – quintic medium with $\delta = -0.1$.

Fig.4.11. shows the evolution of fundamental soliton pulse in fiber core 1 and core 2 in cubic quintic medium with quintic nonlinearity equal to -0.01 and other higher order effects .we observed that the exchange of power takes place in fiber core 1 and fiber core 2.in the start, the input signal is in fiber core 1.As the signal propagates through the fiber coupler, the modal fields overlap which results in transfer of power between both cores .So the optical soliton pulse is switched back and forth along the length of coupler which results in periodic transformation of power between the fiber cores.

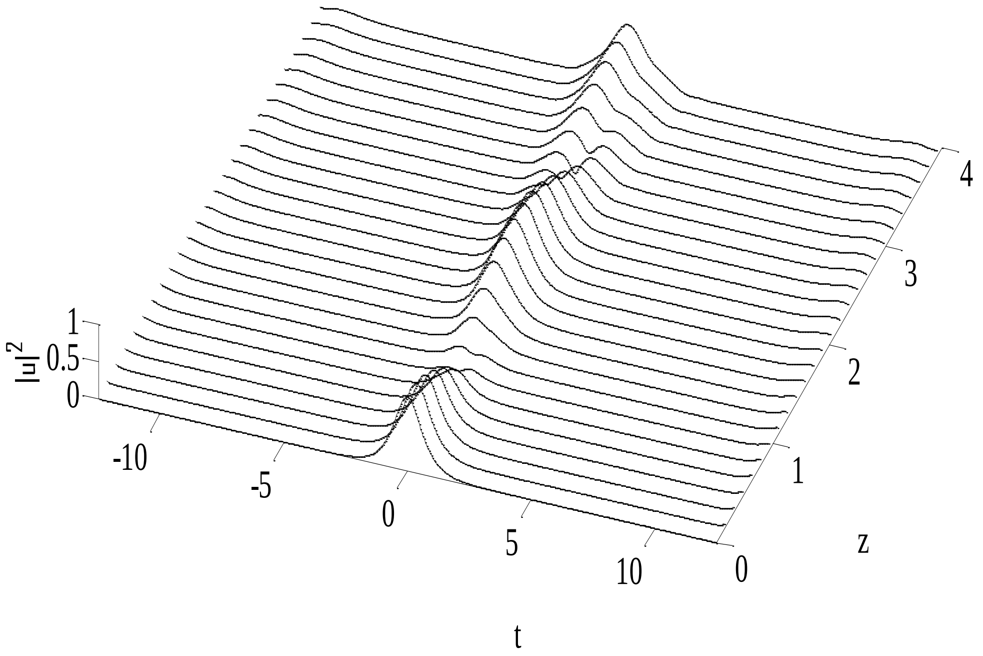


Fig.4.12. Evolution of soliton u along the propagation length of the nonlinear directional coupler (NLDC) in cubic – quintic medium with $\delta = -0.9$.

Fig.4.12. shows the evolution of fundamental soliton pulse in fiber core 1 when high value of first order coupling coefficient dispersion in introduced in system. we found that it results in increase in intermodal dispersion phenomenon and pulse shape distorts as it propagates in fiber coupler. We found that pulse distortion increases with propagation distance in nonlinear fiber directional coupler.

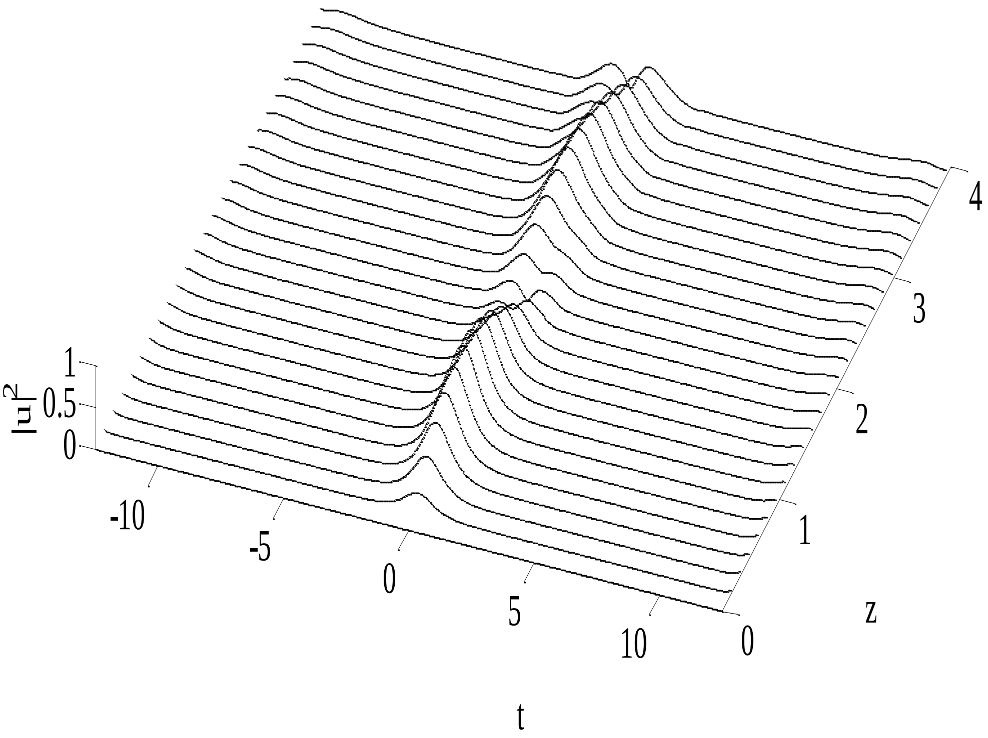
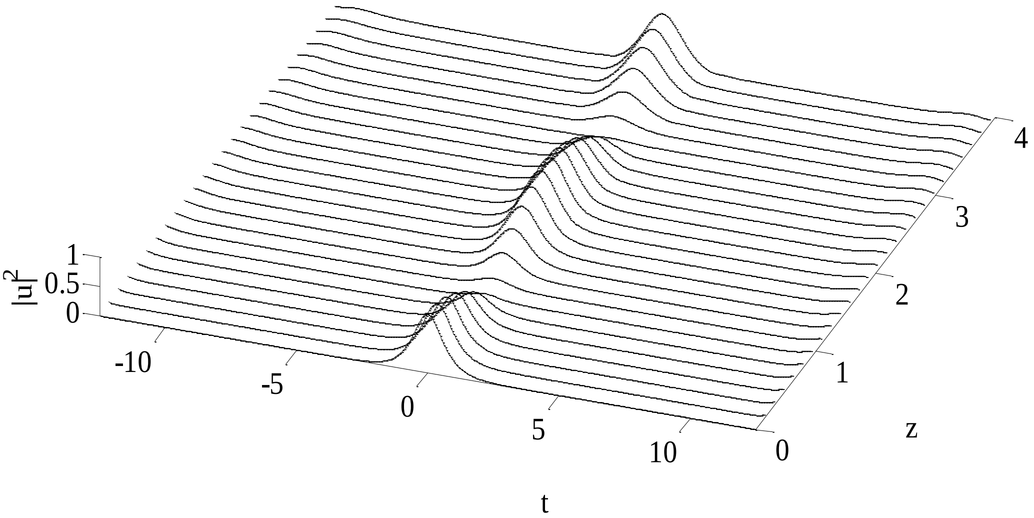


Fig.4.13. Evolution of soliton *v* along the propagation length of the nonlinear directional coupler (NLDC) in cubic – quintic medium with $\delta = -0.9$.



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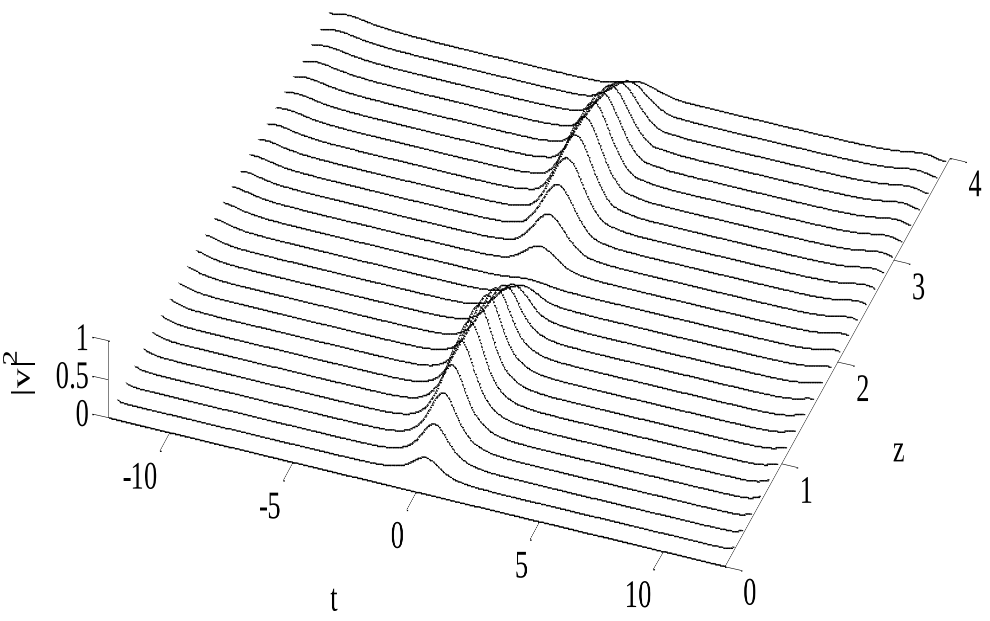
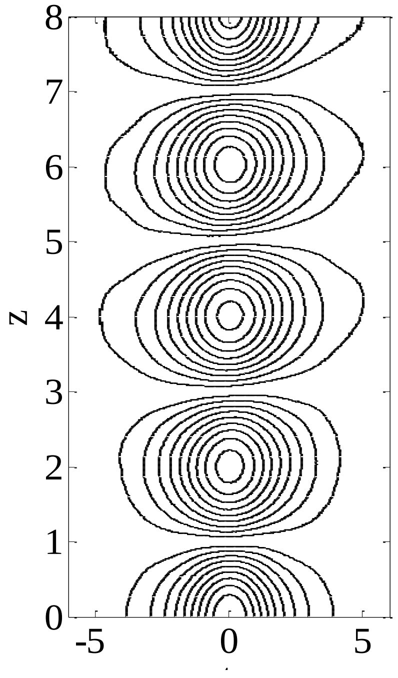


(b)

Fig.4.14. Evolution of solitons *u and v* along the propagation length of the nonlinear directional coupler (NLDC) in cubic – quintic medium in presence of 5 percent random dispersion

It is shown in Fig.4.14, how the fundamental soliton pulses evolved in fiber core 1 and core 2 in cubic quintic medium with quintic nonlinear medium with random dispersion equal to 5 percent. We found that the pulse shapes remains faithful as they were in case of absence of random dispersion in fiber cores. So we can tolerate random dispersion upto 5 percent in design of nonlinear directional fiber coupler.Fig.4.15 shows the contour plots of intensity in fiber core 1 and fiber core as function of propagation distance as soliton input pulse signal propagates. From these contour plots we get excellent observation about the signal behaviour inside the fiber coupler. We found the pulse intensity remains concentrated as it was in input pulse at launching time and we don’t get any extra amplitude peaks along the propagation distance and switching of power back and forth between fiber cores. Also the signal pulse maintain its soliton behaviour and it does not dispersed as it travel the distance .So we get excellent switching characteristics with same input signal back in desired output port.



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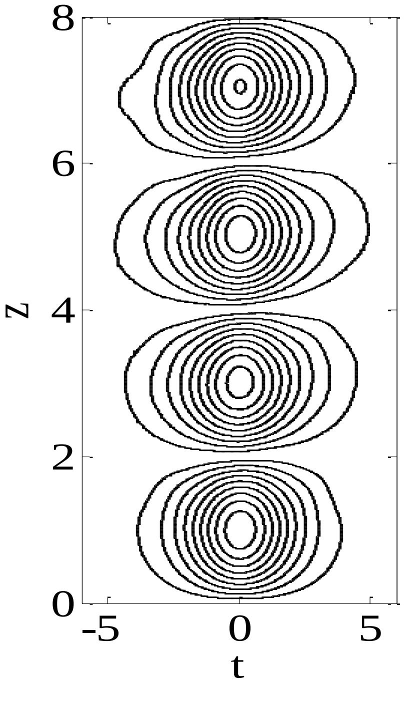
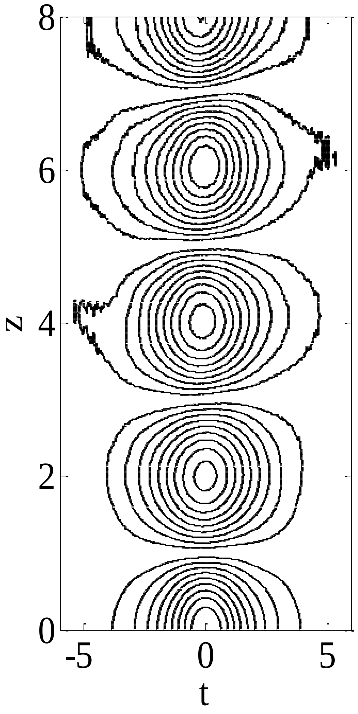
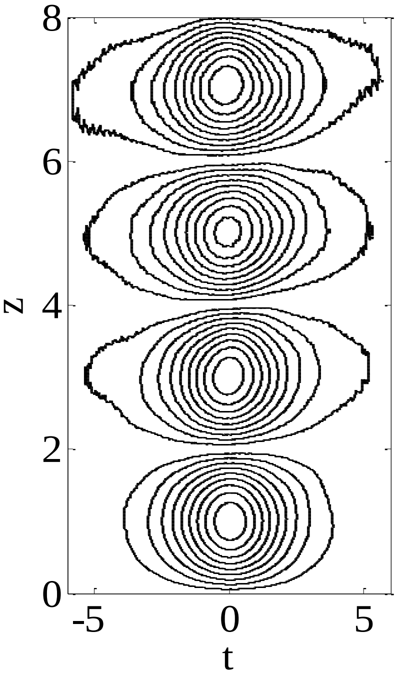


(b)

Fig,4.15 . Contour plots of evolution of solitons *u* and *v* along the propagation length of the nonlinear directional coupler with 5 percent dispersion (a) u (core -1) (b) v(core- 2)



(a)



(b)

Fig 4.16. Contour plots of evolution of solitons *u* and *v* along the propagation length of the nonlinear directional coupler with 30 percent dispersion (a) u (core -1) (b) v(core- 2)

The contour plots of evolution of solitons in fiber core-1 and fiber core-2 in presence of 30 percent random dispersion are shown in fig.4.16. It is clear from the figure that increase in random dispersion leads to distortion in soliton pulse shapes as they got switched back and forth in nonlinear directional fiber coupler during periodic exchange of power. We found that we can’t allow random dispersion in our system beyond certain limit.

CHAPTER 5

Conclusion and Future Scope

This work focuses on performance analysis of nonlinear directional fiber coupler in presence of random dispersion and higher order nonlinear effects. We investigated fiber coupler in presence of third order dispersion and higher order nonlinear effects which are intrapulse Raman scattering and self steepening effect. The performance of nonlinear directional coupler is analyzed taking into account the effect of intermodal dispersion .We investigated the effect of quintic nonlinearity on performance of nonlinear directional fiber coupler. We draw following conclusions from our analysis

1. Quintic nonlinearity has detrimental effect on switching characteristics of NLDC. The switching characteristics of nonlinear directional fiber coupler distort as value of quintic nonlinearity increases. We found that to get sharp switching characteristics the value of quintic nonlinearity should be less than one percent of Kerr nonlinearity.
2. The dynamics of NLDC changes significantly as the random dispersion effect increases. In our study we increase random dispersion from 5 percent to 30 percent. We observed that as random dispersion increases the switching characteristics of nonlinear directional coupler deteriorates sharply. The random dispersion creates chaos in switching dynamics of fiber coupler and it should be taken into account in designing of nonlinear fiber directional coupler.
3. In our analysis, we found that random dispersion up to 5 percent can be very well tolerated in designing of Non linear Directional Fiber Coupler. When random dispersion is 5 percent the switching characteristics remains almost same as in case of zero random dispersion. It is helpful in designer point of view.

The future scope of our work is that the results could be used by designers of nonlinear fiber directional coupler considering effect of random dispersion. The work can be further extended in study of three core couplers and multi core couplers in presence of random dispersion. The nonlinear directional coupler can be used in designing of all optical logic gates. The performance of optical logic gates based on fiber coupler can be analyzed in presence of random dispersion.

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