ANALYSIS OF NONLINEAR DISPERSIONS IN OPTICAL SYSTEM

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ANALYSIS OF NONLINEAR DISPERSIONS IN OPTICAL SYSTEM

A Project

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Department of Electrical & Electronics Engineering
Abstract

of

ANALYSIS OF NONLINEAR DISPERSIONS IN OPTICAL SYSTEM

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Navaneeth Kumar Beeram

The main objective of this project is to analyze nonlinear effects in optical fiber and to
discuss how these effects cause dispersion in input signals. This project also discusses the
pros and cons of nonlinear dispersion. Nonlinear dispersion may be advantageous in
improving the performance of an input signal at the receiver side but may be
disadvantageous in restricting the transmission rate through an optical system. The
nonlinear effects were simulated with the OPTSIM tool and analyzed using the eye
pattern method with respect to bit error rate and Q factor. Simulation results of the
OPTSIM tool were also compared with the numerical analysis of nonlinear effects using
non-linear Schrödinger equation, which is coded and simulated in MATLAB.

_______________________, Committee Chair
Russell Tatro, M.S

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Date

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Chapter 1

BACKGROUND AND INTRODUCTION

1.1 Background
When an optical signal is transmitted through long haul communication systems (the transmission of a light signal over fiber for distances typically longer than 100 km) of optical fiber, a significant distortion will be seen in the received signal. Distortion could be result of chromatic and polarization mode dispersion in Time Division Multiplexing (TDM) and fiber nonlinearity’s in Wavelength Division Multiplexing (WDM) impact transmission performance. Nonlinear effects play a major role in optical fiber with respect to transmission capacity and performance of the system. To achieve maximum transmission rate, combination of TDM and WDM is used and optimized configuration of combination depends on few factors such as dispersion and optical signal power. There are upsides and downsides of using nonlinear effects in optical fiber.[4]

1.2 Introduction
This project deals with analysis of reducing nonlinear dispersion induced distortion in single mode, nonlinear fiber and Erbium Doped Amplifier (EDFA). Analysis of various fiber nonlinear designs are done and compared with each other performances over long haul of 100 km. The designs are simulated using OPTSIM tool. Coding of Nonlinear Schrödinger’s equations are done in MATLAB. Project consists of three phases. First phase deals with introduction to types of fibers, modulation techniques, dispersion, fiber
losses, and dispersion compensation methods. Second phase deals with fiber nonlinearities, advantages, disadvantages, Eye diagrams, BER and Q-factor. Third Phase deals with comparison of various fiber nonlinear designs and their simulation with respect to eye diagram and execution of nonlinear Schrödinger equations in MATLAB.
Chapter 2

INTRODUCTION TO OPTICAL FIBERS AND SIGNAL DEGRADATION

An optical fiber is made up of a core, cladding and buffer coating where the core carries light pulses, the cladding reflects light pulses back into the core and the buffer coating is used to prevent core and cladding from being damaged. Optical fiber is advantageous over the metal wires as it can transmit the data over longer distance with less loss of data sent, higher bandwidth (data rates of 10-40 Gbps) and high resistance to electromagnetic noise. The basic structure of an optical fiber is shown below.[1]

![Optical Fiber Diagram](image)

Fig 2.1 Optical fiber[1]

The diameter of the core is smaller than cladding and buffer coating as shown in fig 2.1. The basic parameter of optical fiber is “refractive index”. Refractive index, defined as ratio of speed of light wave and phase velocity of the wave in the medium. It varies with respect to different mediums (air, water etc).[1]
2.1 Types of Fibers

There are two types of fibers depending on material variations of the core. Step index fiber and graded index fiber. In Step index fiber, uniform refractive index of core is maintained throughout the fiber and abrupt change is seen at cladding boundary, which results in light rays arriving separately at receiver side. Graded index fiber, refractive index of core varies with the radial distance from fiber axis. These fibers are further divided into singlemode (or monomode) and multimode fibers with respect to step and graded index fiber. Single mode fiber carries only one mode of propagation whereas a multi mode fiber carries more than one mode of propagation. However with multimode step index fiber, signals arrive at different times resulting in the pulse spreading causing “intermodal dispersion”. To overcome the dispersion in step index fiber we use multimode graded index fiber. Below are the structures of different type of fibers.[1]
2.2 Fiber Losses

Optical fiber losses results in attenuation of optical signal. Attenuation is defined as loss of optical power of signal transmitted over long distance (due to longer fiber). Loss of optical power is due to material absorption, scattering and waveguide imperfections. Attenuation changes with respect to operating wavelength and fiber type. Attenuation of single mode fibers is less when compared to multi mode fibers. The expression for attenuation is given by\[8\]

$$\text{Attenuation} = -\left(\frac{10}{L}\right)\log_{10}\left(\frac{P_o}{P_i}\right) \quad [8]$$

Where $P_i =$ Optical input power, $P_o =$ Optical output powers, $L =$ Length of transmission distance (Km)

Attenuation units are expressed as “db/km”. The causes of fiber losses are explained below. [8]
2.2.1 Material absorption losses

Absorption is an important factor for signal loss in fiber. Attenuation results when light is absorbed at particular wavelengths, which is converted and dissipated in the form of heat energy. Few of the causes for absorption losses are intrinsic and extrinsic material properties. Intrinsic absorption occurs when there are no imperfections and impurities in an optical fiber and this sets the minimum level of absorption. Extrinsic absorption are caused due to adding the impurities like iron, chromium to the optical fiber during the fabrication process. Extrinsic absorption occurs by electronic transition of ions from one energy level to another level. Both intrinsic and extrinsic absorption can exists in any region of wavelengths. [8]

2.2.2 Scattering losses

Scattering is reflection of light in all directions (it might be out of core or reflected back to source) when it travels through the fiber. When these reflected light rays interact with density fluctuations (produced during manufacturing of optical fibers) within fiber, scattering losses occur. Doping concentration is also one of the factors causing scattering losses because if fiber doped with higher concentration leads to higher losses. [8]

Fig2.5 Scattering losses [8]
2.2.3 Bending losses

Twisting or bending the fiber leads to signal loss. Bending losses are categorized into Microbend and macrobend, depending on radius of bend curvature of fiber. Microbends occur due to the minor discontinuities or fiber imperfection. Fiber imperfections are due to improper manufacturing of the fiber or non-uniform pressures created during fiber cabling. Imperfections in the core cause the reflected light wave to refract in unintended directions (deviates from original path of the light ray). These bending losses are still observed, even after the fiber is straightened after the initial deformation. [8]

![Fig 2.6 Bending losses](image)

Macrobend losses occur when there is larger bend in the fiber cable. Larger bend can be defined as the radius of bend curvature is greater than fiber diameter. This results in higher attenuation of the signal, leads to high amount of signal loss. [8]
2.3 Fiber Dispersion

If a light signal is transmitted over a long haul optical fiber, its power is dispersed with respect to time which widens shape of the pulses in the signal with time. This is called as “Dispersion” (pulse broadening) of the signal. Below is the visual representation of widening shape of the pulse when transmitted through fiber.[2][1]

![Fig 2.7 Dispersion in fiber [1]](image)

Signal dispersion is seen due to multiple modes in the fiber, fiber material, waveguide of fiber and nonlinearities in fiber . [2]

2.3.1 Modal Dispersion

Modal dispersion can be seen in multimode fibers as it’s a result of differences in group velocities of different modes in the multimode fiber. The group velocity is defined as velocity at which data is transmitted along the wave and is given by expression[2]

\[ V_g = \frac{\partial \omega}{\partial \beta} \]

\[ \omega = \frac{2\pi c}{\lambda} \]
Where $V_g$ = group velocity of a wave, $\omega$ = angular frequency, $\beta$ = propagation constant, $c$ = velocity of light (m), $\lambda$ = wavelength of the fiber (nm)

Modal dispersion also referred as “Intermodal dispersion” as it is the distortion caused by differences in delay times of the all modes. Time delay of a mode is defined as ratio of length of fiber and group velocity of the same mode and given by expression [2]

$$\tau_q = \frac{L}{V_g}$$

Where $\tau_q$ = time delay of mode “q”, $V_g$ = group velocity of mode “q”, $L$= length of fiber

Dispersed RMS pulse width can be calculated with an estimated expression

$$\sigma_r \approx \frac{1}{2} \left[ \frac{L}{V_{\text{min}}} - \frac{L}{V_{\text{max}}} \right]$$

$V_{\text{min}}$ and $V_{\text{max}}$ are smallest and largest group velocities and $L$ is the length of the fiber.

Polarization mode dispersion is a form of modal dispersion, in which different polarizations of light in waveguide travel at various speeds because of the imperfections and irregularities causing pulse spreading of the optical pulse.[2]
2.3.2 Material and Waveguide dispersion.

Another kind of dispersion is due to the material of the fiber is known as “Material dispersion”. Optical pulse is combination of spectral components, which operates at their respected wavelengths for a given mode. These spectral components propagate with different speeds depending on their wavelengths. As refractive index varies with the optical wavelengths, material dispersion occurs. RMS value of width of pulse spread by material dispersion is given by [2]

\[ \sigma_r = |D_\lambda| \sigma_\lambda L \] [2]

\[ D_\lambda = -\frac{\lambda_0}{c_0} \frac{d^2 n}{d\lambda^2} \] [2]

Where \( \sigma_r \) = width of pulse spread, \( L \) = length of the fiber, \( n \) = Refractive index of medium, \( \sigma_\lambda \) = width of the source pulse, \( D_\lambda \) = Material dispersion (ps/km-nm)

Waveguide dispersion is another type of dispersion seen in the fiber. It occurs when a signal travels in a waveguide, which has irregular geometry and structure and refractive index is independent of wavelength [4]. Expression for width of pulse spread and waveguide dispersion is

\[ \sigma_r = |D_w| \sigma_\lambda L \] [2]

\[ D_w = \frac{d}{d\lambda_0} \left( \frac{1}{\nu} \right) = -\frac{\omega}{\lambda_0} \frac{d}{d\omega} \left( \frac{1}{\nu} \right) \] [2]

\( D_w \) = Waveguide dispersion, \( \lambda_0 \) = Wavelength of the fiber, \( \nu \) = frequency of signal
Material and waveguide dispersion together referred as “Chromatic dispersion”. Chromatic dispersion is an intramodal dispersion because pulse broadening is related with only single mode of the fiber.\[1\][2]

2.3.3 Nonlinear dispersion

If intensity of light goes high, refractive index of the core will be very much dependent on intensity, resulting in nonlinear effects in the material. These nonlinear effects are seen in the form of phase shifting of an optical pulse. Nonlinear dispersion produces a frequency chirp, is a signal whose frequency varies with time. [2]

All these dispersions affect the transmission rate (bit rate) over fiber. Dispersion can be compensated using dispersion compensation techniques such as dispersion compensation fibers etc. [2]

2.4 Optical fiber transmission link

The key elements of optical transmission link are transmitter block, optical channel and receiver block. Below is shown block diagram. [1] Transmitter consists of optical source, modulation and drive circuit.
In the transmitter block, data in is generated by random generator and sent to drive circuit (electrical generator) to represent the signal in Return to Zero (RZ) or Non Return to Zero (NRZ) format. The output of the drive circuit and output of the light source is send to modulator block to modulate the optical signal (from light source). Connectors are used to provide the interface between transmitter block to transmission medium (optical channel) and transmission medium to receiver block. Optical channel comprises of optical fiber as transmission medium and optical amplifier. Optical amplifier is used to boost the optical signal without converting to electrical signal. These amplifiers are doped to ensure reliable data with the increase of transmission distance. Photo detectors and signal restorer are in the receiver block. Photo detectors (mostly photodiodes) are used to sense the light signals and convert them to electrical signal (current/voltage). Signal restorer is used to extract the signal from noise-induced signal.[1]
In an optical system, obtaining the maximum transmission rate is possible by merging TDM and WDM concepts as it depends on temporal and spectral characteristics of light. However, TDM has limiting factors in terms of chromatic and polarization mode dispersion whereas WDM has limiting factors in terms of the non-linear effects for the transmission performances in the fiber. Optimized maximum transmission capacity depends on a few factors such as dispersion, signal power and fiber length. [7]

Nonlinearity in optical fiber is caused due to high intensity of light in the core. There are two possibilities for the occurrence of nonlinear effects in optical fiber. They are due to inelastic-scattering phenomenon or due to change in the refractive index of the medium related with intensity of light.[5]

Fig 3.1 Types of nonlinear effects [5]
Non-linear effects have their own advantages and disadvantages. These effects limit transmission capacity and can be overcome by using large core fibers, reverse dispersion fibers etc.[7]

On the other side, these effects can be used to improve the performance of the system by wavelength conversion, Nonlinearity in the refractive index is known as Kerr nonlinearity, producing a carrier-induced phase modulation of the propagating signal, which is called the Kerr effect. Refractive index is a function of electric field $E$ denoted by $n(E)$. The function of refractive index is evaluated by Taylor’s series given by

$$n(E) = n + \frac{dn}{dE} + \frac{1}{2} \frac{d^2n}{dE^2} E^2 + \ldots.$$

For symmetry material, first order term of $E$ is zero as refractive index is an even function. Second order is consider to study the Kerr effect and given by an expression

$$n(E) = n - \frac{n^3 \xi}{2} E^2 \quad [2]$$

Where Kerr coefficient is given by

$$\xi = \frac{1}{n^3} \frac{d^2n}{dE^2} \quad [2]$$

$n= \text{refractive index of the medium}$

Typical value of Kerr coefficient is $10^{-18}$ to $10^{-14} \frac{m^2}{V^2}$

Kerr nonlinearity further gives rise to three different effects based on input signal power such as [7][5][2]
3.1 Self-Phase Modulation (SPM)

Nonlinear effect depends on intensity of light and refractive index. Input pulse travels through fiber, which has high intensity of light inside core resulting in higher refractive index. Signal intensity changes with respect to time leads to variations in refractive index with time, which is similar to intensity dependent refractive index. These variations in refractive index resulting in time dependent phase changes. These phase changes are the same as optical signal change with time, so the name Self Phase Modulation (SPM). Different parts of the input pulse change the phase of the signal randomly, resulting a frequency chirp, which is defined as a signal whose frequency varies with time (increases-up chirp or decreases-down chirp). These variations in frequencies cause pulse broadening, which can be seen significantly high in the systems with high transmission power because the transmission power is directly dependent on frequency chirp. [5]

Phase shift by field over fiber length is given by

$$\varphi = \frac{2\pi nL}{\lambda} \quad [5]$$

Where $n =$ refractive index of the medium, $L =$ length of the fiber, $\lambda =$ Wavelength of the optical pulse, $nL =$ Optical path length

In SPM, pulse broadening is seen in the time domain and spectral characteristics are unaltered. Chirp produced by SPM is used to reduce the effects of dispersion caused by pulse broadening. These effects depend mostly on Input power of the signal transmitted,
which can be used as a threshold condition for the frequency chirp to occur. SPM is major limitations in single channel systems. [5]

3.1.1 Applications of SPM

Applications of SPM are solitons and pulse compression. A soliton is a short duration pulse which does not change during the propagation because of cancelling linear and nonlinear effects. In SPM, a frequency chirp generated from linear dispersion in which the leading edge has lower frequencies and trailing edge has higher frequencies and vice versa for chirp generated from nonlinear dispersion. There is a possibility to compensate these effects by varying shape and power of the pulse. [5]

Pulse compression is seen when chromatic dispersion is positive and leading edge of pulse travels slowly and narrow down the gap between leading edge and centre. It is same with the trailing edge but instead it moves slowly it moves faster and comes closer to centre of the pulse. [5]

3.2 Cross Phase Modulation (CPM)

Cross phase modulation is similar nonlinear effect to self phase modulation except it occurs when there are two or more optical signals propagate through fiber. The distortion of signal and pulse broadening will be asymmetric because of more than one signal is propagating and depends on intensity of the propagating pulse and co-propagating pulses. “CPM converts power fluctuations in a particular wavelength channel to phase fluctuations in other co-propagating channels”. [5]
Expression for phase shift caused by nonlinear effect is given by

\[ \phi_{nl}^i = k_{nl} L_{eff} \left( P_i + 2 \sum_{n \neq i}^N P_n \right) \]  [5]

N = N-channel transmission system, \( n = 1, 2, 3 \ldots N \), \( L_{eff} \) = Effective length of link

\( k_{nl} \) = Propagation constant

CPM is better over SPM for propagating transmission capacity twice but it is advantageous only when all the propagating signal are superimposed with each other for every time slice. If the signals are not superimposed, it can lead to severe damage to the system performance when compared to SPM. [5]

3.2.1 Applications of CPM

One of the applications of CPM is “Pulse Compression”. CPM also produces frequency chirp, which is used for pulse compression same as SPM but for SPM, the signal has to be stronger to generate frequency chirp, it is not same with the CPM as it can produce the frequency chirp from a weak signal too because of co-propagating pulses. Phase shift due to CPM is used for Optical switching. Optical switching is used to block the transmission if the phase shift between the pulses is too large and if they are phases of the signal are identical then it will vary the phases of signal using CPM. [5]
3.3 Four Wave Mixing (FWM)

In this nonlinear effect, three optical fields when propagated through fiber will give rise to a new optical field, which depends on the three optical fields, which it was originated from. The frequency of the new optical field is given by [5]

$$\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3$$

\(\omega_1, \omega_2, \omega_3\) are the frequencies of three original optical fields

FWM is not dependent on bit rate as the other two nonlinear effects, instead they depend on channel spacing and dispersion of fiber. Dispersion depends on wavelength, so newly generated optical wave and reference signal wave have different group velocities. With different group velocities, phase matching is not possible, which decrease power transfer to new optical wave. At the same time, if the newly generated wave and original wave has same wavelength, results in interference. The interference of the signals decreases signal to noise ratio. Whenever we observe different group velocities then FWM effect decreases, channel spacing increases and so does dispersion. [5]

3.3.1 Applications of FWM:

Applications of Four Wave Mixing are wavelength conversion and squeezing.

Wavelength conversion is important because when an incoming signal wavelength is already utilized by some other wave and is residing at the destination, then we can change the wavelength by using wavelength conversation technique and allow both signals to
travel through fiber at the same time. FWM is used to squeeze the signal i.e., reducing the quantum noise. [5]

3.4 Comparison of nonlinear refractive effects

Table 1. Comparison of nonlinear refractive effects [5]

<table>
<thead>
<tr>
<th>Nonlinear Phenomenon’s</th>
<th>SPM</th>
<th>CPM</th>
<th>FWM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bit rate</strong></td>
<td>Dependent</td>
<td>Dependent</td>
<td>Independent</td>
</tr>
<tr>
<td><strong>Origin</strong></td>
<td>Nonlinear susceptibility</td>
<td>Nonlinear susceptibility</td>
<td>Nonlinear susceptibility</td>
</tr>
<tr>
<td><strong>Effects</strong></td>
<td>Phase shift due to pulse itself only</td>
<td>Phase shift is due to co-propagating pulses</td>
<td>New waves are generated</td>
</tr>
<tr>
<td><strong>Shape of broadening</strong></td>
<td>Symmetric</td>
<td>May be symmetric or asymmetric</td>
<td>--------</td>
</tr>
<tr>
<td><strong>Channel Spacing</strong></td>
<td>No effect</td>
<td>Increases on decreasing the spacing</td>
<td>Increases on decreasing the spacing</td>
</tr>
</tbody>
</table>

In conclusion, nonlinear effects degrade the performance of fiber optic systems. They provide gain to some channels by increasing transmission rate but at an expense of depleting power. SPM and CPM affect only phase of the signals and can cause spectral broadening, which leads to increased dispersion. The nonlinear effects depend on transmission length, intensity. [5]
3.5 Nonlinear Schrodinger Equation:

Nonlinear Schrodinger equations is used to analyze the non linear behavior of signals propagating in an optical fiber as it includes the physical effects, dispersion and nonlinearity, of the propagating signal. [6]

The basic form of NLSE is

\[
\frac{\partial A}{\partial z} + \frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} = i \gamma |A|^2 A - \frac{\alpha}{2} A \tag{6}
\]

where \( A = A(z,t) \) is a amplitude of a Gaussian input pulse and is associated with the electric field \( E \) of an optical signal in a fiber. Propagation of Gaussian pulse in fiber is consider by taking initial amplitude of that pulse, which is given by

\[
A(0,t) = A_0 \exp \left[ -\frac{1 + i C}{2} \left( \frac{t}{T_0} \right)^2 \right] \tag{3}
\]

Where \( A_0 = \) peak amplitude, \( C = \) Chirp factor, \( T_0 \) and \( t \) are the input pulse width and time period of the wave travelled.

\( \beta_2 = \) Group velocity dispersion coefficient, \( \alpha = \) fiber losses db/km, \( \gamma = \) Nonlinear coefficient.

Nonlinear coefficient is calculated using an expression

\[
\gamma = \frac{n_2 \omega}{c A_{\text{eff}}} \tag{6}
\]
Where \( n_2 \) = refractive index of cladding and depends on refractive index of core, \( \omega = \) angular frequency, \( c = \) speed of light, \( A_{\text{eff}} = \) core area of fiber.

3.6 Eye diagram:

Eye pattern is called Eye diagram, since visual representation of pattern is in the shape of an eye. Eye-pattern technique is a method, which is used to asses maximum transmission rate of a system. Major application of eye pattern is in the optical fiber data links. Eye pattern is measured in time domain and an oscilloscope is used to view the effects of distorted signal. Eye pattern is combination of repeated signals samples generated at output [1]. Typical eye diagram is shown in Fig 3.2.

![Fig 3.2 Typical eye diagram [1]](image-url)
Important features of an Eye pattern are [1]

1) Height and width of eye

2) Overshoot logic zeros and ones

3) Jitter in eye pattern

4) 20-80% rise and fall time

Width of eye opening defines sampling of received signal without distortion. Higher width explains less distortion of signal at receiver. Height (opening) of eye explains distortion of the amplitude in the signal. If height of eye is small, then signal with asymmetric amplitude is received at receiver. Jitter in the eye pattern occurs due to phase distortion and noise in the system. Eye pattern is displayed with boundaries named logic 1 and logic 0. If the eye pattern is observed above or below, the logic levels called as overshoot of logic 0 and 1. These are studied as signals with amplitude higher than amplitude of input signal. Rise time indicates time taken by a signal to reach from 10% to 90% of its amplitude and Fall time indicates time taken by a signal to reach from 90% to 10% of its amplitude [1]. In Fig 3.3 and Fig 3.4, difference between a degraded and ideal eye pattern is shown.

Fig 3.3 Ideal eye pattern [3]
3.7 Bit Error Rate

Bit error rate is defined as “number of errors occurring over a certain period of time by total number of pulses transmitted during this interval” and given by [1]

$$BER = \frac{N_{\text{error}}}{N_{\text{total}}}$$  [1]

Typical error rate of BER for optical fiber communication is in the order of $10^{-9}$. The error rate depends on signal to noise ratio determined by Q factor. The relation between BER and Q factor is given by [1]

$$BER = \left( \frac{1}{\sqrt{2\pi}} \right) \left( \frac{e^{-\frac{Q^2}{2Q}}}{Q} \right)$$  [1]

If Q factor of the system or design increases then BER decreases (BER and Q factor is inversely proportional), means signal received with small noise factor at receiver.
Chapter 4
INTRODUCTION TO OPTSIM TOOL AND SIMULATION MODELS

4.1 Introduction to OPTSIM tool

Optsim is a CAD environmental tool developed by Rsoft for drawing and simulating the schematics of the WDM, TDM, and DWDM based design models. Optsim designs are block-based designs, which are interconnected with the wires. The tool is useful in analyzing nonlinear effects with respect to dispersion, noise, jitter etc. Optsim has two types of simulation modes namely single and block mode simulations. In block mode simulations, data signal is carried out as a block of data between the blocks of the design transmitted between the blocks. Advantage of block mode is easy switching between time domain and frequency domain with the data sent as a block between the optical design models. In sample mode, the input data signal is sent over the design blocks of the model in the form of single sample for every time step. Advantage of sample mode is it can cover unlimited sequence length of data signal when compared to block mode in which data signal is of limited length represented as a block. Sample mode simulations are done in time domain. Performance analysis is done by using eye diagram, BER and Q factor parameters and tools used in optsim tool are spectrum analyzer, scopes (electrical and optical) and signal analyzer.[4] The few component block model icons of design in Optsim are graphically shown as
Designing of model in optsim starts with creating the project and selecting that project to be run in sample mode or block mode configuration because each mode of simulation has their dedicated design component blocks. Next step would be drawing the schematic to design a model and setting up the parameters locally or globally by editing their properties. Then simulate the design and observe the graphs and numerical values, use those as base results for basic design done and optimize the design by playing with the parameters of the blocks in the existing design. Usage of Optsim tool gives you greater accuracy of the design model and capable of varying power parameters easily.

Simulations in optsim tool depend on embedded spice engine, which simulate the electrical circuit from the combined component design model [4]. To simulate the designs in optsim tool, one needs a dongle and license file. Both are correlated using a serial number provided by Rsoft.

4.2 Simulations of various nonlinear effects

All the design models are from Rsoft manual that were used for simulations and analysis. In this section, we will discuss simulations of design models for three different nonlinear effects namely SPM, CPM, FWM in sample mode because these are time varying nonlinear effects. Sample mode deals with time domain simulations. The time domain...
simulations has two types of simulation modes, they are VBS (Variable bandwidth) and SPT (spectral propagation technique). All simulations are done in VBS mode not in SPT. SPT mode is used to evaluate optical spectrum and SNR whereas VBS mode is used to full time domain simulation including linear effects, nonlinear effects and losses. Lower and upper limits of wavelength and frequency are declared in this simulation parameters [4]. All optical signals are with respect to frequency and electrical signals are with respect to time which are discussed in the further sections.

4.2.1 Self Phase Modulation

The design model for the self phase modulation in OPTSIM tool is shown below.

![Fig 4.2 Design of Self Phase Modulation](image)

The design model contains transmitter, receiver and fiber channel blocks.

4.2.1.1 Transmitter block

The transmitter block contains Random data generator, Non Return to Zero (NRZ) modulation, Bessel filter, continuous wave laser, Mach-Zehnder amplitude modulator,
booster, and optical splitter component blocks. Random data generator is used to generate bits randomly, which are transformed to signal using modulation techniques. Commonly used modulation techniques are Non Return to Zero (NRZ) and Return to Zero (RZ). In NRZ, all 1’s are represented by positive voltage and all 0’s are represented by negative voltage. In RZ, signal returns to zero for each pulse with respect to logic level (1 or 0). Here I used NRZ modulation (Digital signaling) technique to generate a signal. Each component block has its own parameters apart from the parameters of the design called as “global parameters”, which are helpful if we want to use the same parameter for two or more components in the model. The transmission rate of the design is set using the random data generator component block. Two types of NRZ modulation exists in the tool, NRZ rectangular and NRZ cosine raised. The inputs for this block are logical bits and it outputs an electrical (digital) signal. NRZ rectangular has an instantaneous switching from one level to another (low to high and vice versa) where as NRZ cosine raised will be gradually switching between logic levels. NRZ modulation block has few basic parameters to be set. One of the parameter is setting the duration between the bits, converted to signal format at the output and other are logic levels which needs to be initialized. The CW laser block is used to generate the optical light signal wave. Wavelength, frequency, power of the signal is initialized and phase parameter of the signal is set to random in this block. The output of the NRZ modulator is sent to Bessel’s filter. The filter is used to preserve the shape of the wave when transmitted within in the pass band mainly with the phase response. The configuration of filter is set to “low pass filter” which passes all frequencies with respect to cutoff frequency (3db frequency in
this filter configuration) and attenuates high frequency signals than cutoff. In this design, 3db frequency is same as bit rate to ensure every signal is passed through filter and preserve the shape. I placed the electrical oscilloscope to observe waveforms before and after the Bessel’s filter with the 3db, frequency of filter is set to same as transmission bit rate. The filter is more effective when the higher transmission rate.

Output of Bessel’s’ filter is shown in Fig 4.3, which is visualized as almost a sinusoidal waveform (not an instantaneous switching between levels). The output of filter and CW laser are sent to amplitude Mach-zehnder modulator, is an electro-optical modulator used to modulate the light wave with respect to transmitted electrical signal and generates an
optical signal at the output of modulator. Chirp factor of the signal is defined in the modulator block. The modulated signal is sent to booster (an optical amplifier), which is used to boost power of the signal with the factor set in booster block configuration. The optical signal before and after the booster block with factor 10 is shown below.

Fig 4.4 Input optical signal of SPM
The optical signal after booster is amplified with the factor 10 which was defined in the block and can be seen visually in the above graph (factor 10 was with respect to power, show on Y-axis). This signal is sent to optical splitter which is then sent onto many sub design models with equal division of optical power if the losses are set to zero. The design shown in the Fig 4.2 has only one sub design. To generalize the things, optical splitter is used in the above design so that we can add sub designs in the future for the same design. An optical scope is connected at the output of optical splitter to observe the optical signal. Fig 4.5 is the Input optical signal, transmitted to the fiber channel.
4.2.1.2 Fiber channel

Fiber channel in the design is shown as iterative loop component. The iterative loop component consists of fiber, fiber compensating technique component and In-line optical amplifier. The components in the iterative loop block are show below.

![Fig 4.6 Components inside iterative loop [4]](image)

The iterative loop is used to resend the signal within the block depending on iteration number. Iteration number is set in the iterative block properties. When the components are made as a compound block, they need to be connected by input and output ports inside the compound block. Use of an iterative loop makes the design more reliable and aids in the observe of the quality of output signal by increasing the fiber length. The Fig 4.6 also has input and output port within the compound block. The input optical signal is send over the fiber. The fiber has few important parameters, which needs to be considered and configured. They are Length of the fiber, losses, dispersion coefficient, nonlinear effects and nonlinear coefficient. Output of the fiber is sent to fiber grating, which is used to compensate the distortion of signal by inducing dispersion after each stage. Fibers grating compensator is used to reflect particular wavelengths of light and transmits others, achieved by varying refractive index (varying intensity of light). Dispersed signal is then sent to an Inline optical amplifier to amplify signal. Inline optical
amplifiers are used for simple amplification because effect of dispersion is small when we use single mode link fiber. [4] The intermittent waveforms after each stage of fiber are shown below. The output signal after the fiber without passing through fiber grating and amplifier is shown as first iteration waveform in Fig 4.7.

Fig 4.7 Signal received after fiber_first iteration

Fig 4.8 Signal received after fiber_second iteration
We can observe that after finishing first iteration through fiber, the signal is similar to input signal, which is shown in Fig 4.7. After the first iteration, signal is sent through ideal fiber grating to reduce dispersion and retain the signal. Iteration number repeats the process of sending the signal through fiber. In the fig 4.8 and fig 4.9, optical signal is dispersed by factor X after each iteration. Output signal from the fiber channel is sent to the receiver block through out-multi port, a compound output port and the waveform is shown in Fig 4.10. The difference between Fig 4.5 and Fig 4.10 is the dispersion of the optical signal caused by the fiber channel.
4.2.1.3 Receiver block

The main blocks of the receiver system are raised the cosine Gaussian optical filter, a photodiode, a Bessel filter and an electrical oscilloscope. The raised cosine filter is used for pulse shaping to minimize intersymbol interference. The output signal from fiber channel will be an input to raised cosine filter. Filter configuration is set to band pass filter. The band pass filter is used to transmit all the frequencies within the specified range. The photodiode is used to convert an optical signal into an electrical signal. There are two types of detectors, pin (positive intrinsic negative) and APD (avalanche photodiode). PIN detectors are considered because they have zero internal gain. Main factors of photodiode are quantum efficiency and responsivity where responsivity depends on
wavelength and quantum efficiency. Quantum efficiency is the percentage the photons hit the surface to produce electron hole pair. In normal conditions, photodiodes operate in reverse bias. Output of photodiode is sent to Bessel’s filter, whose 3db frequency is configured to 80% of the bit rate because the NRZ modulator roll off factor (slope) is 0.8 as it is the property of the ideal modulator that it generates 80% of the input value at the output depending on switching between levels (0 and 1) [4]. Electrical scope is used to capture the output electrical signal, eye pattern. Eye pattern measurements are collected in time domain. All the Component blocks are connected through wires.

4.2.1.4 Simulations
The basic simulation parameters of the SPM design and its simulation results are discussed in this section. The transmission rate is set to 10 Gb/s, amplitude of input signal range is set -2.5 to 2.5 V, The power of the light wave is set to ~4mW, fiber length set to 100km, wavelength is set to 1550nm, so frequency is calculated by expression \( \nu = \frac{c}{\lambda} \) which is equal to 193.4 Thz. The filtered electrical input signal show in Fig 4.4 is combined with the light wave to generate an input optical signal. The optical signal shown in Fig 4.8 is transmitted over the fiber channel, dispersion is compensated using the fiber grating technique but due to the SPM effect in the fiber, pulse broadening is observed at the output. Dispersed optical signal shown in Fig 4.11 is then sent to receiver unit to convert optical signal to electrical signal. The output electrical signal is captured using electrical scope. The transmitted signal power decreases as the signal travels
through the design, output signal power is less than the transmitted signal but the signal phase and shape is preserved. The input waveform is show in the Fig 4.4 and the output waveform is shown in the Fig 4.11

From Fig 4.12, amplitude of the signal is decreases with the decrease in power, which is observed in output optical pulse. The loss of power causing attenuation of the signal with respect to amplitude, results in distortion of signal. The eye pattern is shown in Fig 4.12. Eye pattern is generated by overlapping the samples of signals. The eye jitter in the below figure is very less which implies noise level or distortion in the signal is very less. There is no zero level noise in the eye pattern as the distortion is at the higher level of the signal and the lower level of the signal is received without distortion.

![Fig 4.11 Output electrical signal of SPM (10Gbps)](image-url)
As SPM effect depends on bit rate, let us observe the optical signal before and after the fiber channel by increasing the bit rate to 40 Gb/s. The waveforms of optical signal after fiber channel and Gaussian filter is shown in Fig 4.14, Fig 4.15. Due to high bit rate, optical signal has lower frequency components to the original signal. Gaussian filter configuration is set to band pass filter. Due to the band pass nature, the filter excluded the low frequency components and passes frequency components of signal, which exists in the pass band range shown in Fig 4.15. Optical signal shape looks similar to input pulse without any low frequencies.
Fig 4.13 Optical signal before fiber channel with 40Gbps

Fig 4.14 Optical signal after Gaussian filter with 40Gbps
The electrical output signal and eye pattern is shown in the below figures.

**Fig 4.15 Output electrical signal of SPM (40Gbps)**

**Fig 4.16 Eye pattern of SPM (40Gbps)**
The waveforms show that the output signal is distorted with the increase of bit rate due to the increasing of SPM effect. The eye pattern is looks messy due to the noise effects and one can concludes that the signal is distorted by excessive noise as shown by the eye jitter and eye height. The same behavior is seen if we decrease the laser power to one micro watt and have the bit rate as 10 Gb/s.

As said earlier, the fiber-grating block compensates dispersion, which is seen in the fiber channel. I want to discuss the importance of compensation of the dispersion in the fiber.

The earlier design of fiber channel shown in Fig 4.6 has fiber grating block. Let us remove the fiber grating block and have only fiber and amplifier block in the new fiber channel design. After simulating with the new fiber channel, the waveforms of output signal and eye pattern are shown in Fig 4.17 and 4.18. The signal is totally induced with noise and signal is totally distorted which is shown in Eye pattern. Dispersion in the fiber and SPM effect causing the distortion, to overcome distortion use fiber grating block to compensate the dispersion of the fiber at every stage of the design with respect to fiber.
Fig 4.17 Output electrical signal without fiber grating

Fig 4.18 Eye pattern without fiber grating
4.2.2 Cross Phase Modulation.

Cross phase design model is similar to Self-phase design except the transmitter block has two WDM (wavelength division multiplexing) channels. Design model is shown in Fig 4.19. Cross phase modulation is nonlinear phase change due to optical signal in other channel. Description of the component blocks in the below design is discussed in the SPM section.

Fig 4.19 Design of Cross Phase Modulation [4]

4.2.2.1 Transmitter block

There are two channels named high and low power channels to differentiate the input signals from each channel. Cross phase modulation is advantageous over the SPM is
because it has two channels with the same bit rate. The input signals waveforms of high power channel and low power channels are shown in Fig 4.20 and Fig 4.21.

Fig 4.20 Input electrical signal for high power channel

Fig 4.21 Input electrical signal for low power channel
These two signals are combined with light wave to form an optical signal with respect to the each channel. The two optical signals are then combined to form a single optical signal representing two signals, which is shown in the Fig 4.22. The optical signal having two signals is carried to booster block to amplify the signal.

Fig 4.22 Optical signal resulted from two different channels

The first signal seen in the Fig 4.22 is from high power channel and other from low power mode channel.

4.2.2.2 Fiber channel

The fiber channels contain fiber, fiber grating and optical amplifier with fixed gain. Optical Amplifier with fixed gain (Inline optical amplifier) is not to amplify signal but to
focus on fiber transmission properties. Optical signal shown in Fig 4.22 is transmitted over the fiber channel and dispersion due to fiber is compensated at each stage of the fiber. In Fig 4.19, there is a two stage fiber channel and the output of the fiber channel is shown in Fig 4.23. The signal is dispersed due to the cross phase modulation effects over the fiber channel.

4.2.2.3 Receiver block

Dispersed optical signal is transmitted through Cosine raised Gaussian filter which behaves as band pass filter as per the configuration of filter. The filter outputs the signal, by passing the frequencies specified in the filter block configuration. The signal is shown in the Fig 4.24. The signal generated by band pass filter is sent to a sensitive receiver, which acts as a PIN photo diode, converts optical signal to electrical signal. The output electrical signal is captured using an oscilloscope.

![Fig 4.23 Dispersed optical signal](image-url)
The electrical output signal and eye pattern are also shown in Fig 4.25 and 4.26.
In the Fig 4.25, the electrical signal is combination of low and high power channels. With different power channels, the eye pattern is not clear and has lot of jitter and overshoot on logic 1. With equal power channels, the eye pattern looks less distorted when compared to Fig 4.26. Simulation parameters are similar to the SPM simulation parameters except the logic levels of signal are defined as zero and 5V. The CPM also depends on bit rate and seen the same behavior as SPM, when we increase bit rate. Pulse broadening may or may not be symmetry in CPM (pulse broadening will be symmetry if the channels has same power and vice versa).
4.2.3 Four Wave Mixing

Four wave mixing effect is also performed with two or more WDM channels. In this design model, there are two WDM channels. Signals generated from these channels are used to generate new signal with the new frequency. Design model of FWM is shown in Fig 4.27.

4.2.3.1 Transmitter block

In Fig 4.27 there are two channels with different laser power to differentiate the input pulses. Design of transmission block and fiber channel of FWM is same as CPM transmission block and fiber channel. The only change in the FWM is the first channel has lower power of light wave than second channel (we can have first channel as high power channel and second as low power channel). These signals sent to optical modulator.

Fig 4.27 Design of Four Wave Mixing [4]
along with light wave. Input optical signal is observed at output of optical splitter and shown in Fig 4.28

Fig 4.28 Input optical signal of FWM

4.2.3.2 Receiver block

Receiver block is also similar to CPM except it does not have Gaussian filter after optical splitter. Because the design of FWM receiver does not have any filter and signal is not attenuated to limited frequencies, instead the original output optical signal is sent to the photodiode. The optical signal seen at the output of optical splitter at the receiver side is shown in the Fig 4.29 and the outputs of oscilloscope are shown in Fig 4.30 and Fig 4.31. In Fig 4.29, we can observe that there is another optical pulse in the signal generated from the two input optical pulses. From the eye pattern, eye opening can be calculated which indicates the output signal distortion is not dominating the signal strength. Eye
jitter is considerably low compared to CPM eye pattern. Only amplitude of the output signal is distorted.

Fig 4.29 Output optical signal of FWM

Fig 4.30 Output electrical signal of FWM
4.3 Optimization of optsim tool

The models designed by the optsim tool are nominally optimized. Consider an SPM design in optsim tool developed by Rsoft. One of the factors to discuss optimization of design would be usage of filters. The design model of SPM shown in Fig 4.2 can be designed without the filters if we use the transmission rate of 10Gbps or lower. However, if we increase the bit rate, then we need filters to exclude the unwanted signals (noise) generated due to high bit rate. Another factor would be signaling techniques. All three designs I discussed in this project have the modulation technique as NRZ signaling modulation. There are few signaling technique such as RZ, NRZ, Manchester. The optsim tool has RZ and NRZ signaling type. All the designs models discussed earlier uses
NRZ signaling. Instead, design model for SPM can be designed using RZ signaling and see what would be the impact on the designs and output. Simulating design with RZ signaling broadens the input pulse more than NRZ signaling format while the configuration of design remained unchanged. The designs and parameters in the designs by Rsoft in the tool are nearly optimized as by trying different design methods and varying parameters in the existing design results in loss of signal or signal induced with noise and higher rate of dispersion (pulse broadening of a pulse is high with time). These effects are shown in Fig 4.32 and Fig 4.33.

Fig 4.32 Input optical signal with RZ signaling
Fig 4.33 Output optical signal with RZ signaling
Chapter 5
COMPARISON OF NONLINEAR EFFECTS AND MATLAB

5.1 Comparison of nonlinear effects

In this section, I will compare all three nonlinear effects and conclude which nonlinear effect is more advantageous and why. Comparisons are based on Q factor. The nonlinear dispersion due to SPM is considered advantageous only when one WDM channel is used. One has to compromise with the transmission rate and number of channels in the design. More channels leads to reduction in the transmission rate for an optimized design. I placed a Q estimator at the end of each design (SPM, CPM and FWM) to assess the Q factor and Eye pattern features of the designs. From the Fig 4.12, the distortion of the signal is not significant as the width of jitter is not too thick and visually represents a shape of human eye. The results from the Q estimator block give a clear idea. The Q factor for SPM design model is 23.412. Q factor (used to specify system performance) is related to SNR and inversely proportional to BER. To calculate BER value from Q factor generated from design, I wrote a software algorithm in Matlab to calculate BER with any value of Q factor. High Q factor shows that the signal is less immune to noise and received signal is similar to input signal with less noise.

SPM nonlinear dispersion effects is advantageous over other nonlinear dispersion effects which will be discussed further but SPM design is only with one WDM channel. In today’s world, challenge is to have more than one channel and higher transmission rate to receive the signal without distortion when transmitted through fiber link. To achieve
above, we will be considering CPM and FWM dispersion effects. As discussed earlier, CPM and FWM designs have two WDM channels in the design. CPM and FWM has different power for each channel. The eye pattern shown in Fig 4.27 for CPM has Q factor of 2.64673, which is close to ideal Q factor value of 1.9876 and has less value of eye opening. This is observed because of different amplitudes of signal with respect to power. I have the same power for both channels; can see the improvement in the Q factor from 2.64673 to 2.314. CPM dispersion effect achieved of having more than one WDM channel but was not quite enough to receive the signal with less noise at receiver. CPM effect causes serious distortion in the signal. In FWM effect, high improvement of Q factor is seen at the expense of eye opening, which is due to generation of new signal at a cost of power. Value of Q factor for FWM design is 56.784, which ensures that the noise level present in the signal is negligible. The FWM dispersion effect achieves more than one WDM channel and better reception of signal with different power levels in the channels at receiver. I conclude that, FWM nonlinear dispersion effect is more advantageous and effective when compared to SPM and CPM. The units (numbers) of Q factor discussed are linear not in decibels. Summary of the parameters observed using electrical scope and Q estimator in Optsim tool is given in Table 2.
Table 2. Comparison of nonlinear effects using practically implemented design in Optsim tool

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SPM</th>
<th>CPM</th>
<th>FWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit rate</td>
<td>10Gbps</td>
<td>10Gbps</td>
<td>10Gbps</td>
</tr>
<tr>
<td>Channels</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Q factor (linear)</td>
<td>23.30125</td>
<td>2.64673</td>
<td>56.58847</td>
</tr>
<tr>
<td>Q factor in db</td>
<td>27.3478</td>
<td>8.45418</td>
<td>35.0545</td>
</tr>
<tr>
<td>Eye opening</td>
<td>0.16773e-1</td>
<td>0.11536e-3</td>
<td>0.79394e-2</td>
</tr>
<tr>
<td>Eye Jitter</td>
<td>0.0142e-9</td>
<td>0.0240e-9</td>
<td>0.0145e-9</td>
</tr>
<tr>
<td>BER</td>
<td>1e-40</td>
<td>5.605e-17</td>
<td>1e-40</td>
</tr>
<tr>
<td>Sampling time</td>
<td>0.052ns</td>
<td>0.016ns</td>
<td>0.064ns</td>
</tr>
</tbody>
</table>

5.2 Split step algorithm and Matlab

The numerical analysis of these nonlinear effects is done by Nonlinear Schrödinger equation. The equation is solved using an algorithm called “Split-step algorithm”, which is coded in Matlab. Split step algorithm separates linear and nonlinear parts of the equation as shown below and solves it separately.

The nonlinear Schrödinger equation is given by [6]

$$\frac{\partial A}{\partial Z} + \frac{i \beta_2}{2} \frac{\partial^2 A}{\partial t^2} = i \gamma |A|^2 A - \frac{\alpha}{2} A$$ [6]
We can rewrite the above equation as

\[
\frac{\partial A}{\partial Z} = -\frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - \frac{\alpha}{2} A + i\gamma \left| A^2 \right| A \quad [6]
\]

Representation of above equation after dividing into linear and nonlinear parts is

\[
\frac{\partial A}{\partial Z} = -\frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - \frac{\alpha}{2} A + i\gamma \left| A^2 \right| A = \left[ D + N \right] A \quad [10]
\]

When \(\gamma=0\), results in linear part of nonlinear Schrödinger equation

\[
\frac{\partial A_D}{\partial Z} = -\frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - \frac{\alpha}{2} A = DA \quad [10]
\]

Consider \(\alpha=0, \beta_2=0\), results in nonlinear part of nonlinear Schrödinger equation

\[
\frac{\partial A_N}{\partial Z} = i\gamma \left| A^2 \right| A = NA \quad [10]
\]

Added a small step “h” simulation parameter is added to separate the linear and nonlinear terms of the equation with minimal error. If we solve nonlinear part of equation in time domain will result as [10]

\[
A_N(t, Z + h) = \exp \left[ i\gamma \left| A \right|^2 h \right] A(t, Z) \quad [10]
\]

In the same way, solving the equation of linear part gives us

\[
A(\omega, Z + h) = \exp \left[ \frac{i\beta_2}{2} (\omega)^2 h - \frac{\alpha}{2} h \right] A_D(\omega, Z) \quad [10]
\]

The linear function is solved in Matlab and then took inverse Fourier transform of the linear function and multiplied with the nonlinear function as both are in time domain. A
Fourier transform is taken to generate the spectrum for combined equation and inverse Fourier transform ensures the propagation of signal. I simulated the code with the parameters from the optsim design model of Self phase modulation to show the ideal behavior of the input pulse compared with practically generated dispersed pulse when transmitted through fiber. Below are the waveforms for the ideal case with the numerical analysis. The parameters are $P_i$ (input power) = 3.98mW, Fiber losses in dB/km = 0.25, Time period of input pulse = 200ps, area of effective core = 67.56, Chirp factor = 0, Wavelength = 1550nm, dispersion coefficient = -10 ps/nm/km and length of the fiber = 100km.

Fig 5.1 indicates input pulse, Fig 5.2 shows us FWHM (Full Width at Half Maximum, defined as width of frequency range where at least signal power is half the maximum) points on input pulse. FWHM points are observed at half of the power, if amplitude is calculated with power of signal, if amplitude is calculated with voltage, then FWHM points are observed at 0.707*Voltage. Pulse broadening ratio is defined as ratio of output FWHM to input FWHM. With the help of FWHM’s generated from the code, pulse broadening ratio is plotted. The pulse broadening ratio plot shown in Fig 5.3 explains how the input pulse is broadening with respect to distance travelled. Fig 5.4 shows us the spectral output pulse waveform (pulse broadening is zero for ideal case). Ideally, there is no pulse broadening, when input pulse transmitted through zero dispersion and zero chirp factor in the fiber calculated by numerical analysis but when an input pulse is sent through the fiber, simulation results show dispersion. Numerical analysis of the nonlinear effects ideally shows how the input pulse looks like at the receiver and practical
implementation gives you virtual experience of the dispersion due to fiber seen in the received signal.

Fig 5.1 Input pulse from Matlab (ideal)

Fig 5.2 FWHM points on input pulse
From Fig 5.4, when there is no pulse broadening the received signal will be replicate of input signal considering zero losses.

Parameters considered from reference [3] shows dispersion of the input pulse with respect to distance of fiber in the output spectrum. \( P_i=0.00064 \text{mw} \), \( \gamma=0.003 \).
dispersion coefficient = 1.5684e-5, wavelength = 1550nm, Chirp factor = -2, time period of pulse is 125ps, fiber losses = 0 db/km. Waveforms of input pulse, dispersed pulse and pulse broadening ratio are shown in Fig 5.5, Fig 5.6 and Fig 5.7

Fig 5.5 Input pulse from Matlab (with dispersion)

Fig 5.6 Output spectrum of input pulse (with dispersion)
Fig 5.7 Pulse broadening plot (with dispersion)

Fig 5.6 shows the broadening of the pulse with distance travelled by input pulse.

Output spectrum is an 3 dimensional plot, which has X, Y and Z axis. In the plots shown above, X axis represents “time”, Y axis represents “distance” and Z axis represents “amplitude”. The colors represent the amplitude value of the signal. Using the reference software algorithm from [9], I generalized and optimized the algorithm to take wide varieties of inputs and see the behavior of input signal with respect to those inputs. Output spectrum shown in Fig 5.6, lower frequency components are attenuated using a band pass filter as discussed earlier in simulations.
Chapter 6
CONCLUSION AND FUTURE WORK

6.1 Conclusion
This project dealt with analysis of three important nonlinear effects in optical system. Non-linear effects have disadvantages in the form of limiting the transmission rate but have an advantage of improving performance of transmitted signal in the system. Initially, I discussed the theoretical analysis and comparison of nonlinear effects then practically proved the theoretical analysis of nonlinear effects by simulating the design models in optsim tool developed by Rsoft and compared these effects against each other with respect to Q factor. Later on, short modeling of numerical analysis of nonlinear Schrödinger equation using Split step algorithm is done to analyze the effects of nonlinearity in fiber, which is coded and optimized in Matlab. By performing the simulations in optsim, had a good exposure to the features of tool.

6.2 Future work
All the designs were not physically implemented (using hardware) due to insufficient resources. In future, physically implementation can be done and compare the results of simulations with the results of physical implementation. In addition, further optimization of the designs can be achieved for higher bit rate.
Matlab code [9]

clc;
q=1;
Pi=input('Enter the value of input power in mW  ')
alpha=input('Enter the value of fiber loss in db/km  ')
t=input('Enter the value of input pulse width in seconds  ')
tau=input('Enter time period with upper(U), lower(L) and interval
between upper and lower interval(I) in this format L:I:U')
dt=input('enter intervel of period')
Area=input('Enter the area of effective core in m^2  ')
C=input('Enter the value of chirp factor  ')
Lamda=input('Enter the wavelength in meters  ')
D=input('Enter the value of dispersion coefficient ps/nm/km  ')
s=input('Enter the length of fiber in Km  ')
disp('Fiber losses in /km  ')
A=alpha/(4.343)
c=3*1e8;
n1=1.48;
pi=3.1415926535;
%delta=0.01
delta=(n1*2*pi*s)/Lamda
n2=7e-10
n2=n1*(1-delta)
f=c/Lamda;
omega=2*pi*f;
a=n2*omega;
b=c*Area;
gamma=a/b %calculation of nonlinear coefficient
%gamma=0.003;
B2=-(Lamda^2*D)/(2*pi*c) % calculation of group velocity dispersion
coefficient
L=(t^2)/(abs(B2)) %dispersion length
Ao=sqrt(Pi) % amplitude of an input gaussian pulse

h=2000 % small step as defined by split step algorithm

for ii=0.1:0.1:(s/10) %different fiber lengths
X=ii*L;
At=Ao*exp(-((1+i*(C))/2)*(tau/t).^2); % generation of an gaussian
input pulse
figure(1)
plot(abs(At)); % graph of input pulse
title('Input Pulse'); xlabel('Time in ps'); ylabel('Amplitude');
grid on;
hold off; 

l=max(size(At));

fwhmi=find(abs(At)>abs(max(At)/2)); 
fwhmi=length(fwhmi);
dw=1/l/dt*2*pi;
w=(-1*l/2:1:l/2-1)*dw;
At=fftshift(At);
    w=fftshift(w);
    spec=fft(fftshift(At)); %generating a pulse spectrum
    for j=h:h:X
        spec=spec.*exp(-A*(h/2)+i*B2/2*w.^2*(h)) ; % calculation of linear part
            of NLSE
            f=ifft(spec);
            f=f.*exp(i*gamma*((abs(f)).^2)*(h)); %calculating nonlinear part of
            NLSE
            spec=fft(f);
            spec=spec.*exp(-A*(h/2)+i*B2/2*w.^2*(h)) ; % NLSE calculation
        end
    f=ifft(spec); % pulse propagation
    output_pulse(q,:)=abs(f); %preserving output pulse
    fwhmo=find(abs(f)>abs(max(f)/2));% finding the Full width half maximumof output
            signal
    pbratio(q)=fwhmo/fwhmi; %finding pulse brodening ratio
    q=q+1;
end

figure(2);
    mesh(output_pulse(1:1:q-1,:)); %output spectrum
    title('Pulse Evolution');
    xlabel('Time'); ylabel('distance in km'); zlabel('amplitude');
figure(3)
    plot(pbratio(1:1:q-1)); %pulse broadening plot
    xlabel('distance in km');
    ylabel('Pulse broadening ratio');
    grid on;
hold on;

Code for calculating BER.

Q=input('enter the value of Q factor in db');
Pi=3.14
A=(1/2*Pi)
B=exp(-Q^2/2)
disp('The BER for value of Q is')
BER=A*(B/Q)
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