A

DISSERTATION REPORT

ON

SIMULATION OF FOUR WAVE MIXING USING CHANNEL SPACING AND NON-LINEAR PROPERTIES OF FIBER

is submitted in partial fulfillment for the award of degree of

MASTER OF TECHNOLOGY

IN

ELECTRONICS AND COMMUNICATION

BY

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(2015PEC5070)

UNDER THE GUIDANCE OF

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CERTIFICATE

This is to certify that the dissertation report entitled "**SIMULATION OF FOUR WAVE MIXING USING CHANNEL SPACING AND NON-LINEAR PROPERTIES OF FIBER"** submitted by **SHAILJA THAKUR** (2015PEC5070), in partial fulfillment of Degree **Master of Technology** in **Electronics & Communication Engineering** during the academic year **2016-2017**.To best of my knowledge and belief that this work has not been submitted elsewhere for the award of any other degree.

The work carried out by her has been found satisfactory under my guidance and supervision in the department and is approved for submission.

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LIST OF ABBREVIATIONS

MZI	Mach-Zander Interferometer
WDM	Wavelength Division Multiplexing
DWDM	Dance wavelength Division Multiplexing
CWDM	Coarse Wavelength Division Multiplexing
TDM	Time Division Multiplexing
FDM	Frequency Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
FBG	Fiber Bragg Grating
LED	Light Emitting Diode
LASER	Light Amplification by Stimulated Emission of radiation
SPM	Self Phase Modulation
CPM	Cross Phase Modulation
FWM	Four Wave Mixing
SRS	Stimulated Raman Scattering
SBS	Stimulated Brillouin Scattering

Abstract.

This dissertation describes the non-linear effects of optical fiber i.e. Four Wave Mixing. Optical fiber communication system in long distance communication system is limited by nonlinearity of optical fibers. As along the length of optical fiber these effects assemble in the link and optical fiber has very less threshold value for nonlinear effects. By the less threshold value these effect comes in communication system (Wavelength Division Multiplexing Transmission System).

Due to non-linear effects in optical Fiber system performance is not accurate. When date rate, power, number of channels, and transmission length increases .Nonlinear effect becomes more. So in DWDM this study becomes important .Wavelength division multiplexing is technique which is used in optics to multiplexes many carrier signals into a single optical fiber having different wavelength ,different wavelength means different colors of light that is coming from optical fiber.

Wavelength division multiplexing technique allows bidirectional communication in an optical fiber and multiplexes the capacity. Dense wavelength division multiplexing is a promising technique which is comes to enhance bandwidth and increase the no channels. In DWDM multiple information can be transmitted through single fiber using different wavelength .Due to long cable and high speed during transmission, information (transmitted signal) comes across a type of dispersion called chromatic dispersion

There are mainly two types of nonlinearities occurs in optical fiber:.

1. Due to nonlinear Refractive index effects.

2. Due to Inelastic Scattering effects.

Amount of Change in refractive index and input sign Kerr effect nonlinearities come in three types of effect those depend on nonlinear refractive Index are Self-Phase Modulation (SPM), Cross Phase Modulation (CPM), Four Wave Mixing (FWM).Stimulated –Raman Scattering (SRS), Stimulated Brillion Scattering (SBS) these are due to inelastic scattering at high power level.

In DWDM when channels are equally spaced and close to each other in term of frequency then Four Wave Mixing is dominated nonlinear effect as compared to other effect. But occurrence of Four Wave Mixing needs some desire amount of dispersion in fiber. This phenomenon is similar to that occur in amplifier, when amplifier goes to saturation

Despite of disadvantage there are considerable advantages of Four Wave Mixing in DWDM those are wavelength rotating network for non-blocking situation, and wavelength conversion.

In this thesis combined effect of Length of fiber, Channel spacing and Input power are studied for Four Wave Mixing inside a fiber. Wavelength conversion an application of four wave mixing is performed in optisuystem7. By taking parameter like Bit error rate (BER), Quality factor (Q-factor) and Eye height. By using different cable length and at different bit rate simulation is performed at 1550nm alternatively taking q-factor above 7 and BER blow 10^.9.

Keywords:

Nonlinear Propagation, cross phase modulation, four wave mixing SMF, dispersion compensating fibers, FBG.

Chapter1

Introduction

1.1 Review of Optical Communication System

Optical communication is a process of communication at a distance using light as a medium to carry information from source to transmitter. Communication can be performed visually or by electronics device. An Earlier form of optical communication is done by electronics device photo phone. The optical fiber is one of the most important types of a channel used in Optical communication. Optical fiber communication plays imp role because of its advantageous over another medium those are co-axial medium, microwave link, wires. Advantages of optical fiber over other media are –

a) The amount of information that can be transmitted in optical fiber per unit time is most significant as compared to other transmission media
b) Optical Fiber gives low power loss
c) Optical fiber cables are resistant to electromagnetic interference. In electrically noisy environment also optical fiber communication can be achieved without any much effect.
d) The capacity of optical fiber more and have a less cross sectional area.
e) The light weight of optical fiber and thinner quality makes it easy to install in the communication medium.
f) Information from the optical fiber is not easy to tap because they do not emit electromagnetic energy.

In today there are large population and no. of the user are more so demand of channel bandwidth is more. So By using WDM in optical communication, no of channel per optical fiber link can be increased by DWDM & CWDM. When the optical amplifier is used in the optical link, transmission impairment added to link and becomes a challenge in optical communication design and these impairments cannot be ignored.

Nonlinear effects are more significant in the Optical link they generate dispersion in each WDM channel and produce a crosstalk in one channel due to another channel. SPM (self-phase modulation), XPM (cross phase modulation), SRS (Stimulated Raman scattering) and FWM (Four-wave mixing) are nonlinear effects. Four-wave mixing is a process of generating a new wavelength when two wavelengths are transmitted in a system.

1.2 Background of optical communication-

The process of transmitting information from transmitter to receiver with the help of light pulses through an optical fiber is called optical fiber communication. EM wave used for modulation of the light signal.3rd generation fiber optic communication comes in use at 1.55um and 0.2dB/km losses are calculated. Use of WDM in a system to increase bandwidth capacity & of the optical amplifier to lessen the use of repeater comes in the 4rth generation of fiber optics. 5th generation doing work to increases the wavelength existing range of WDM.

1.3 Basics of optical communication-

Fiber-optic communication is a type of communication in which fiber is used as a transmission media to transmit information from source to destination. Fiber optical transmission is only one choice when we have to transmit Gigabytes or more than gigabytes of data at the time and this is all done through a single fiber. Fiber optic communication system sends data through a fiber and by converting electronic signals into the light signal or optical signals. By fiber optic communication data, voice, and video can be transmitted. Block diagram of fiber optical communication system is shown in figure 1.1. Information source gives the information and this electrical information 1st be converted to optical form by transmitter circuit and then optical information travels through an optical fiber at receiver information which is in optical form detected by detector and converted back to electrical form by photo-detector present in receiver circuit

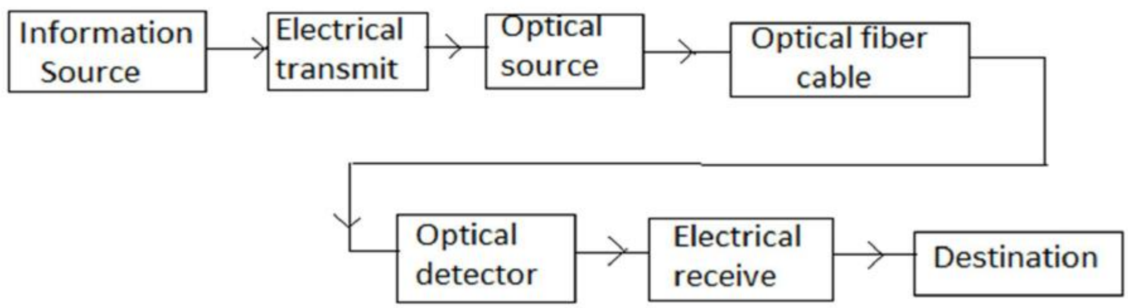


Figure 1.1 Block diagram of optical communication system.

Data from information source given to transmitter circuit which is in electrical form, light sources convert electrical signal to light signal. The wavelength used in fiber optic communication is near to infrared range and just above the visible range so LED & LASER are commonly used light sources to fulfill this requirement. Amplitude, phase, and frequency of source should be stable to minimize alteration or to have the proper transmission. The beam of Light from the light source is carried by fiber optic cable to the receiver circuit and this light signal is changed to the electric signal by photo-detector. Photo-detector is able to calculate phase, frequency, and amplitude of light signal

1.3.1 Element of optical fiber communication system–

There are many blocks in fiber optic communication system but three blocks are basic those are a light source, transmitter, optical fiber, and receiver. Others are Switch, connector, amplifier; Multiplexer, couples .splices and much more are important component in fiber optic communication system

A. Light source-

The optical fiber is a type of cable which is cylindrical in form and dielectric in nature and low loss material. Extruded Glass (Si) or plastic is used to make optical fiber and it is flexible. The approximate diameter of .25mm to .5mm is used to make optical fiber which is comparatively equal to human hair. The width of diameter is decided by the application used.

B. Optical fiber

Fiber optic having four parts that are-Core, Cladding, Buffer and Jacket

a) The Core- Core is made up of plastic or silica and cylindrical in form and follow the cable's length. Light does not go out from the core and reflects from cladding boundaries due to Total Internal Reflection properties. Core shape has to be circular almost for all applications.

b) The Cladding-outer body of the core is cladding used for protection purpose. Through dense material i.e. from core light enters the cladding having less dense material light changes it's bending angle and so comes back to core

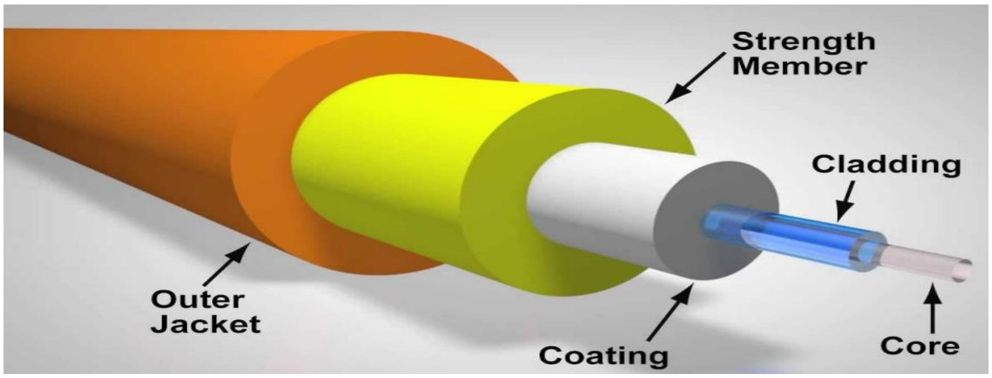


Figure 1.2 Optical fiber

c) Buffer-protects the optical fiber from vandalizing because optical cable contains a number of optical fibers.

d) Jacket-Jacket protects the bundle of fiber i.e. cables. Jackets are found in many different colors. From the color of the jacket, we get to know the color of cable we are working with. Orange color and yellow color of jacket point out Multimode fiber and single mode fiber respectively.

Types of optical fiber- There are two types of fiber based on light propagation inside a fiber and those are single mode fiber and multimode fiber as discussed below-

a) Single mode fiber –It is a type of optical fiber carries light in a fiber –in a transverse mode. In single mode fiber wave having different frequencies, but having the same mode, their distribution in space occurs in the same way, as a result, we get a single ray of light. Single mode fiber used in television and telephones. The core of single mode fiber is small in size.

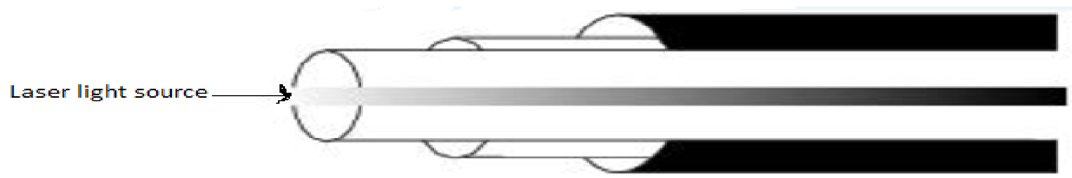


Figure 1.3 Single mode fiber

V number is 2.405 for single mode fiber. Light launching and fabrication in single mode fiber are difficult so single mode fiber is expensive. But the degradation of signal or transmission loss is less in single mode fiber. Single mode fiber is advantageous for long distance communication.

b) Multimode fiber-It is used for short distance communication e.g., in a campus, in a premise or in building having bit rate between 10Mbps to 10Gbps and due to model dispersion link length limited to 600m. Refractive index and Core size of multimode fiber are larger than single mode fiber so multiple light modes can be transmitted through it. No of mode that propagates inside an optical fiber is approximately equal to V^2/2. Fabrication of fiber and launching light to fiber in multimode fiber is easy as compared to single mode fiber

Figure 1.4 Multi-mode Fiber

There are two types of fiber based on the change in refractive index and those are step index fiber and refractive index fiber.

a) Step index fiber –This fiber has a constant core with n1 refractive index and constant cladding with n2 refractive index. Refractive index of the cladding is less than the refractive index of the core. When the refractive index is plotted as a function of distance its shape looks like the step function. The following figure shows the step index fiber.

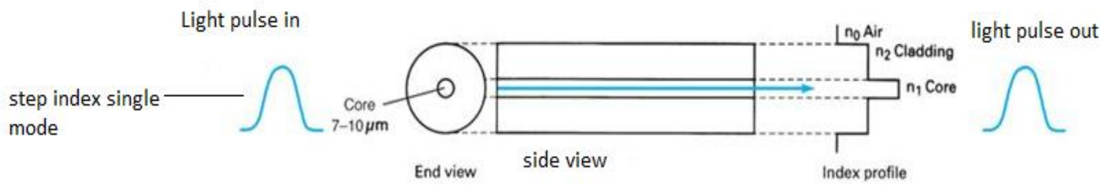


Figure 1.5 Single mode fiber

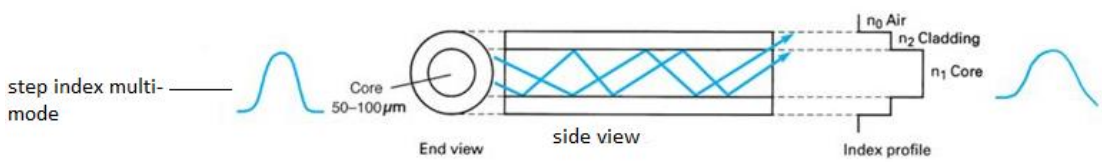


Figure 1.6 Step index fiber

b) Graded index Fiber- In this fiber with the increase in radial distance of refractive index of core decreases. The portion of the core which is closer to the fiber having the higher refractive index and the portion far away have the less refractive index, the light rays look like sinusoidal path while traveling down the fiber. Following diagram shows the graded index fiber

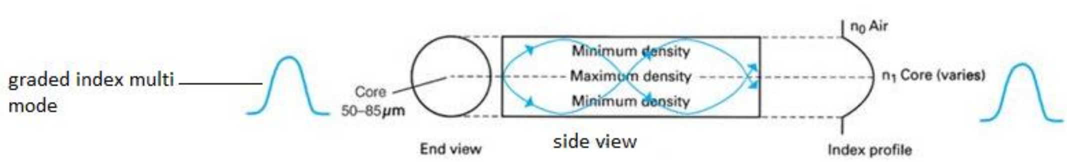


Figure 1.7 Graded index multi-mode fiber

Merits of optical fiber- Optical fiber have many advantages over other communication medium and one of them is carrying capacity and fewer losses due to these advantages optical communication is of interest nowadays. Some of the advantages are following-

a) Bandwidth -Optical fiber has a large bandwidth as compared to other metal cables. The amount of information that can be sent over the transmission medium is very large.

Telecom industry used Signal mode cable for long distance communication. This bandwidth completes the today user needs and has enough bandwidth for future use.

b) Less signal degradation- An optical fiber has less signal loss so using optical fiber we can transmit up to the larger distance.

c) Interference- There is less electromagnetic interference in Optical fiber cable. Optical fiber cable is not affected by Electrical noise so optical fiber can be installed in the electric noisy network.

d) Security-optical fiber is dielectric in nature so spark hazard does not present in Optical fiber.

e) Ease of installation-optical fiber has the very less cross-sectional area as compared to metal wire cable because of optical fiber much thinner and lighter and occupies less space. The optical fiber has 4.5 times more capacity as compared to metal wires. The light weight of optical fiber makes it easy to install in the field.

f) Cost- Material used for Optical fiber like glass is abundant in nature, unlike copper. Means construction cost of making glass is cheaper than copper.

g) The flexibility-tensile strength of the optical fiber is large. It is easy to bend optical fiber because it has flexible nature and it resists many corrosive elements

1.3.2 Multiplexing Technique –

To send no of the signal through the single fiber to increase the capacity of communication and lessen the amount of investment signal are multiplexed and this process is called multiplexing. Multiplexing is a process of combining many signals that may be analog or digital signals, combined for transmission by a single optical fiber. By multiplexing capacity of optical fiber communication systems is increased and time shared by many channels at a time by this cost has been lessened. Demultiplexing process is reversed to multiplexing.

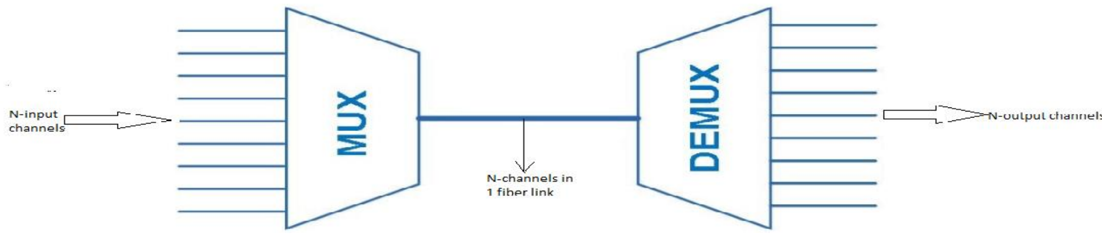


Figure 1.8 Multiplexing & Demultiplexing Of N- Channels in Single Link Of Fiber

Three types of multiplexing techniques are used in optics to enhance the capacity

a) Frequency division multiplexing (FDM)-

In frequency division multiplexing innumerable signal is merge in a single channel or line for transmission. FDM is an analog technique. In FDM different frequencies are allotted to each sub-channel in the main channel. In FDM bandwidth of the main channel is greater than a combination of each subchannel that has to be transmitted.so in transmission medium each subchannel has its own frequency and it makes its own virtual way and follows this way only. The guard band is used to separate these channels. So that signal does not coincide with one other. The guard band is a band of unutilized channels. e.g. Television signal transmission.

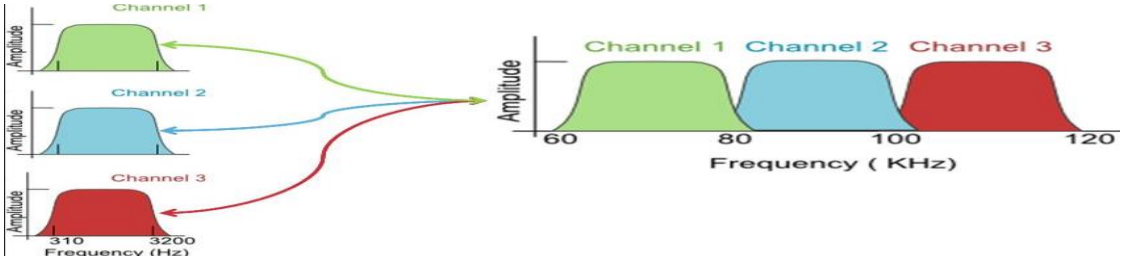


Figure 1.9 Frequency Division Multiplexing

Advantages of frequency division multiplexing, A numerous no of has been transmitted concurrently. There is no need of synchronization between transmitter and receiver for operation. Demodulation process of FDM is easy

b) Time-division Multiplexing (TDM)

It is a process of communication of the independent signal from a transmitter to receiver over a common signal path by breaking the transmitting the signal in segments, such that each segment has a less duration. Every distinctive stream of data is organized at the receiver on the basis of time. It is less efficient because multiple signals are transmitted everyone is sending in on after another, as shown in figure-

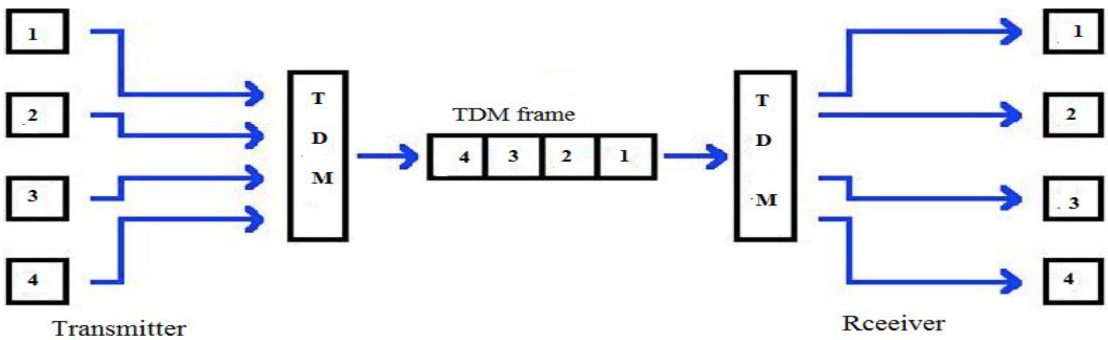


Figure 1-10 TDM Multiplexing

c) Wavelength-division Multiplexing (WDM) –

This is the process of combining the many signals into a single beam at many wavelengths (in IR range) for transmitting the signal across fiber optic medium. Each laser light is modulated by the different set of signals. At receiver wavelength, the sensitive filter has used that sense the wavelength in this range. Bidirectional Communication and capacity multiplexing in the strand of fiber is by Wavelength division multiplexing. A multiplexer is used in the transmitter in WDM system to mix the many signals together and at receiver to separate signal apart demultiplexer is used.

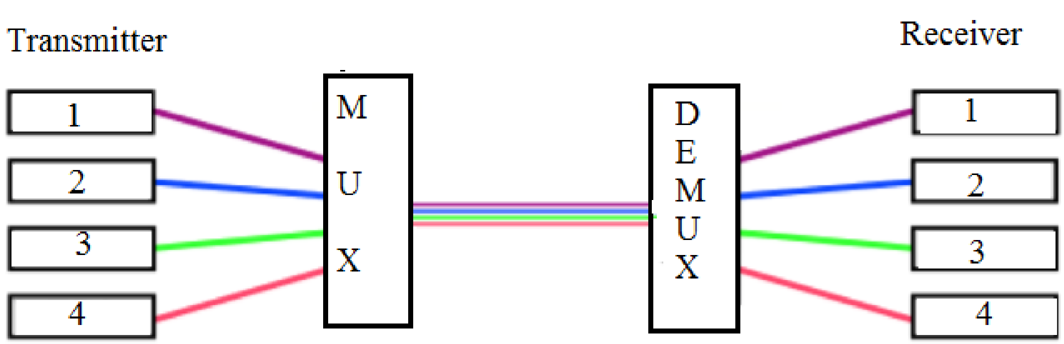


Figure 1.11 WDM Multiplexing

This is the process of combining the many signals into a single beam at many wavelengths (in IR range) for transmitting the signal across fiber optic medium. Each laser light is modulated by the different set of signals. At receiver wavelength, the sensitive filter has used that sense the wavelength in this range. Bidirectional Communication and capacity multiplexing in the strand of fiber is by Wavelength division multiplexing. A multiplexer is used in the transmitter in WDM system to mix the many signals together and at receiver to separate signal apart demultiplexer is used. BWDM (normal WDM), DWDM and CWDM, are types of WDM and differ in a number of channels and have different quality of amplification of multiplexed signal in an optical fiber system.

a) BWDM- Contain two wavelengths 1310nm and 1550nm in one fiber.

b) DWDM -In DWDM bandwidth is increased by multiplexing many signals DWDM uses 18 wavelengths for multiplexing. Originally DWDM has wavelength those have to multiplexed is in the range of 1550nm so that it is possible to take the advantage of EDFA(erbium doped fiber amplifier) as an amplifier because wavelength range of EDFA is magnificent for C-band (1525-1565) nm. Channel spacing of 100GHz is used for 40 channels and 50GHz of channel spacing is used for 80 channels

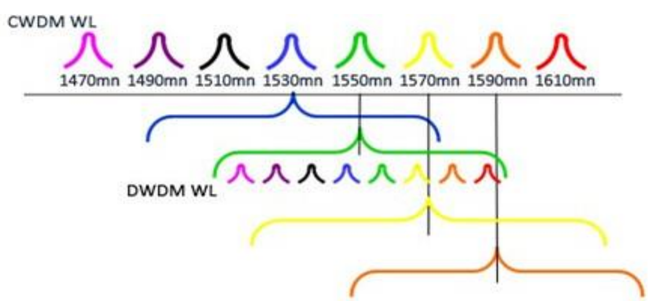


Figure 1.12 Dense WDM Spectrum

c) CWDM -CWDM is used to increase the bandwidth by multiplexing more no of channels wavelength as compared to DWDM. Coarse WDM gives about 16 channels in numerous transmission window of silica fiber. But normally upper 8wavelength from 16wavelength are used.

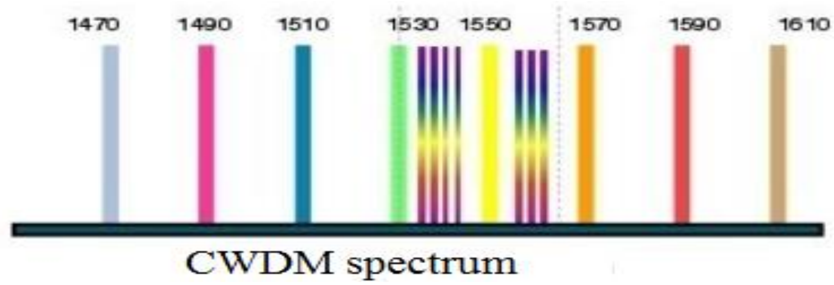


Figure 1.13 Spectrum of coarse WDM

CWDM initially filter the incoming light so that desired wavelength can be used then wavelength has been multiplex or demultiplex in the single link of fiber. To increase the numbers of channels 1550nm band and the 1310nm band is divided into a smaller part, then after dividing each channel has a band that is 20nm wide. Channel spacing of CWDM is larger than DWDM by which cheaper component can be used in CWDM network

1.3.3 Dispersion in Fiber-

Due to Dispersion in optical fiber transmission system, there are distortions in an analog signal as well as digital signal. In Dispersion propagation velocity of an electromagnetic wave is wavelength dependent. So in general broadening original time pulse by imperfection and by properties of materials is called dispersion. There is ISI (inter-symbol interference) effect due to the dispersion which is pulse broadening as they travel along the fiber. When each pulse broaden it overlap with the neighboring pulse and at receiver signal detection becomes impossible. Pulse spreading or overlapping reduce the capacity of optical system.

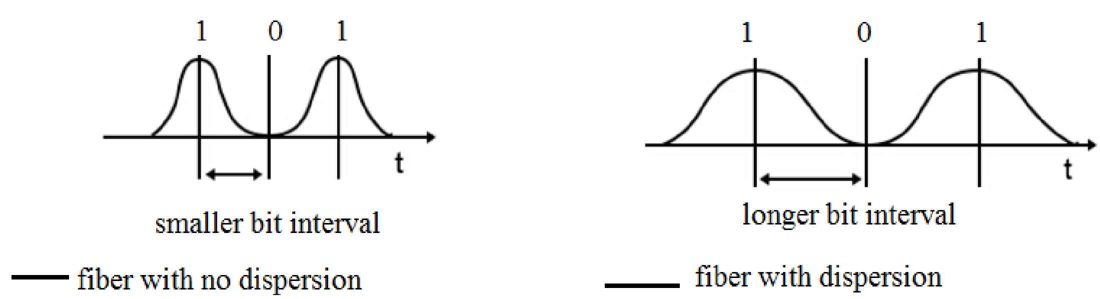


Figure 1.14 Pulse broadening with Dispersion

A) Intermodal dispersion- This is also called modal dispersion. Occurs in multimode fiber, In multimode fiber modes incident at the different angle at core-cladding boundaries, so incident rays have different timing and reached at receiver in different time, as a result there are broadening of the pulse. Intermodal dispersion can be reduced by using single mode fiber in place of multimode fiber but we multimode fiber can also be used but with graded index fiber and lessen core diameter

B) Intra-modal dispersion- Pulse broadening in a single mode fiber known as the intra-modal dispersion or Chromatic dispersion. It is also called group velocity dispersion because it is the wavelength dependent phenomenon and group velocity is the function of frequency. Three main types if intra-modal dispersion are-

a) Material dispersion- When dispersion in pulse comes due to material properties then is called material dispersion. Because here core material is a function of wavelength so there is the change in refractive index or core when an incoming light wavelength is changed. Spectral width is depending on material dispersion in an optical fiber. The number of the wavelength that can be transmitted in fiber core is called spectral width.

b) Wavelength Dispersion- Dispersion arise through waveguide effect (propagation of different wavelength) is called Wavelength dispersion or chromatic dispersion that depend on characteristics of a waveguide, refractive index, and core, cladding shape. This dispersion occurs in single mode fiber here signal power traveling in core and cladding having the different refractive index. Material dispersion is higher than waveguide dispersion so in many cases waveguide dispersion has been neglected

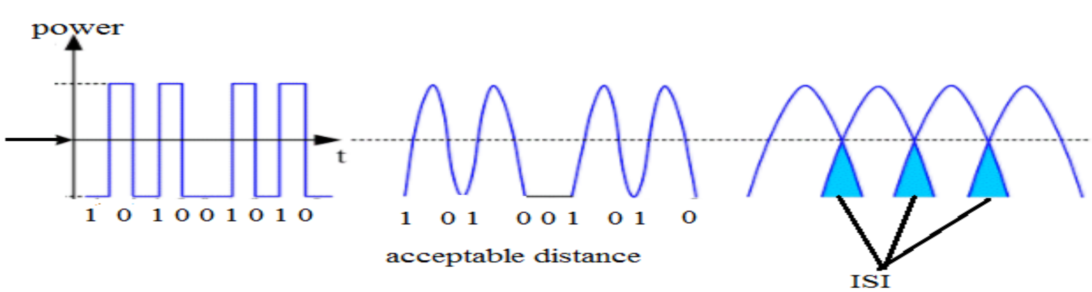


Figure 1.15 Chromatic dispersion

c) Propagation mode dispersion- Due to disfigurement and uniformity two polarization of light not travels with the same speed in a waveguide causing broadening of pulses in an optical fiber .Because single mode fiber has two mode of polarization which is orthogonal each other and in dispersion free fiber both travels with the same speed. When there is birefringence in optical properties means refractive index depend upon polarization and propagation of incoming light and different in x-axis and y-axis .Nonlinearities e.g., self -phase modulation (SPM), Cross-phase modulation(CPM), and four-wave mixing(FWM), effect of these nonlinearities is lessen by dispersion. So in optical system dispersion must not be zero at once, but dispersion has to zero in the receiving side after the long distance. From here there is need of Dispersion Compensation Technique.

1.3.4 Dispersion compensation technique-

Dispersion compensation fiber, Fiber Bragg grating, Electronic dispersion compensation, Digital Filter, Optical phase conjunction technique

A) Dispersion compensation grating-

It is a periodic change of refractive index in the fiber link. This periodic change is called Grating. There is photosensitivity effect after this due to back reflect light from the fiber. For each change in the refractive index, a small portion of the light is reflected back. And at last all portion of reflected light are combined and they must be satisfied a Bragg condition

Bragg's law $n_{eff}\Lambda=\lambda/2$

Here n_{eff}=effective refractive index, Λ=grating period, λ=Bragg wavelength

B) Dispersion compensation fiber-

Dispersion compensation fiber is one of the techniques for dispersion compensation. In this technique, fibers have the dispersion of negative slope as compared to originating dispersion. Dispersion compensation fiber inserted in between transmission line in a regular manner. The problem with DCF is high attenuation. The fiber of 18 to 20 km length can be used to compensation 120 km fiber dispersion, and it gives a 0.8-0.1db/km attenuation. To reduce this attenuation fiber is used in between. So placement of fiber as dispersion compensation in single mode fiber is an idle approach. All effects are wavelength dependent that occurs in Dispersion compensation technique. Hence the design of DCF is for the whole band of wavelength. This dispersion compensation fiber length is so high that no linear effects problem arises. They have the broad bandwidth which is good for WDM work.

1.3.5 Optical amplifier-

To transmit the signal over a 100 km distance or to compensate attenuation losses optical amplifier is used. An optical amplifier is used in the long distance communication system. An optical amplifier is a device which amplifies the optical signal without converting to electrical signal and back to the optical signal. To enhance the signal power level after multiplexer optical amplifier is used. But it also gives losses in the optical system.

In single mode, fiber attenuation losses are more as compared to dispersion losses. So there is no need of complete reconstruction of the signal, amplification process is sufficient to recover the signal. Transmission losses are overcome by an in-line amplifier. Before photodetection a weak signal is amplified by preamplifier so that degradation comes in a signal by thermal noise is suppressed is suppressed, pre-amplifier should be used before the optical receiver. If an optical signal needs enhancement just after the transmitter then power and boosts amplifier area used after the optical transmitter. Reason to use optical amplifier is – Reliability, Flexibility WDM, and low cost, SOA, EDFA, and ramen amplifier are main types of optical fiber

A) Semiconductor Optical Amplifier

Semiconductor optical amplifier is based on the gain of semiconductor medium.In the semiconductor, optical amplifier mirror that is used at the end are changed with a coating that doesn't reflect the light. Still, if there are reflections then waveguide of tilted nature is used to further reduce the remaining reflection from the mirror. The semiconductor optical amplifier is used in much application like regeneration of signal, conversion of wavelength, reshaping of distorted pulses, and to use less power. It has a capability to integrate high component, and volume prefabricate, from this advantage SOA is power effective and cost effective. SOA is generally obtainable in variable form factor for different uses.

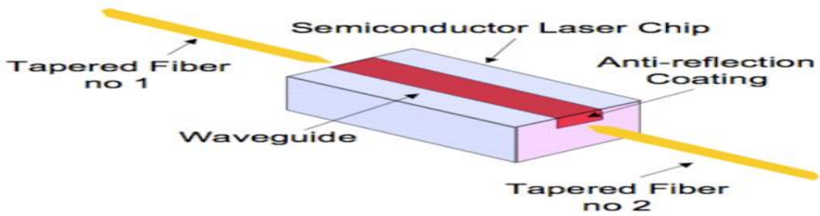


Figure 1.16 Semiconductor amplifier

Stimulated emission is used to amplify the incoming optical signal in semiconductor optical amplifier. To pump photon to in current region electrical pumping is used for stimulated emission process. When the incoming optical signal goes through this active medium these excited electrons gives where the energy to incoming light and has come back to ground level. Both photons have the same energy so signal level goes high or signal is amplified. Gain, gain bandwidth, bandwidth, are main characteristics of SOA. Amplification bandwidth is determined by gain bandwidth product. SOA current the oversee the optical gain

b) Erbium Doped Fiber Amplifier

EDFA amplifier based on the fiber doped with erbium. For long haul communications erbium doped fiber amplifier have a considerable advantage because EDFA properly amplifies the optical light for 1.5 um wavelength range, in this range, there is less loss in optical fiber.

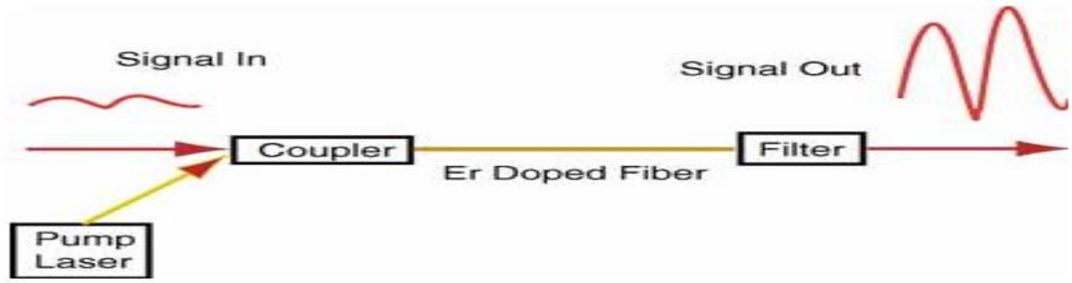


Figure 1.17 Erbium Doped Fiber Amplifier

Erbium doped fiber amplifier is single mode fiber. Pumping can be bidirectional or unidirectional. For unidirectional pumping, pumping in forward directional and in backward direction can be used and bidirectional pumping two laser diodes have been used to pump active medium fiber, pumping is called bidirectional.

1.4 Problem Statement

The long haul network means in public switched networks, belongs to circuits that take a lot of distances, like inter- LATA circuit, and circuit for international communications, required high bit rate for their operation because the demand for bandwidth is increased day by day. The system which has wavelength multiplexing can transmit multiple signals with different wavelengths concurrently. There are many bottleneck issues in the performance of optical communication systems like higher bit rate, input power supply, bandwidth and much more. When the optical fiber is used in a link there are many non-linear effects in the system produced by the nonlinearity of optical fiber.

Stimulated ramen scattering(SRS), Stimulated Brillion Scattering(SBS), Self-phase modulation(SPM), cross phase modulation(CPM), Four-wave mixing(FWM) are some of the nonlinear effects by the optical fiber. These nonlinear effects downgrade the performance of optical communication system. Four-wave mixing is most important factor in the communication system. It is the major restricting factor in WDM network. When no. of the signal goes through the one optical fiber, all signal having the different velocity so they interact with each other, when the transmission distance is less then this interaction is very weak but this interaction increases as transmission length are increases. The FWM is due to the optical Kerr effect, this effect changes the refractive index with the increase in optical fiber. In this thesis there I take the use of this nonlinear effect for wavelength conversion inside a fiber which is used where wavelength routing is needed [17] [18].

1.4 Methodology

To take the use of FWM as a wavelength conversion opti-system is used as simulating software. There are various methods which are used to reduce the four wave mixing effect in transmission Link and these methods are compared and other changes are examined. Power for different fiber length is checked and for different channel spacing. Four-wave mixing at multiple channel spacing is evaluated [16][17].

Simulation is performed for different wavelength in a c-band. By using wavelength converter input wavelength can be changed into the different wavelength. In optical cross connects this wavelength conversion has an important role in the wavelength blocking network. And one of the uses is for eluding the effect of wavelength blocking

When there is fixed number set of wavelength in a network wavelength converter is used for new wavelength as compared to input. By doing this there is a new wavelength at output port which is further use within the network.

1.5 Software used-

Opti-system is a simulation software package in an optical communication system for testing, design, and virtual optimization of the optical link in optical networks. Opti-system has a powerful simulation base and definition of the component of components and systems. It is compatible with Opti wave's design tool opti-Amplifier and OptiBPM. Opti-system has a wide application in WDM network transmitter, receiver design and, channel amplifier. This software does not depend on other software for simulation. It is a simulator of system level which is based on the designing of a communication system of fiber optics. It contains simulation domain and for the understanding of component, the description of each and every component is given [20].

Its abilities can depend on the user. Opti-system analysis parameters are BER and Q-factor as a result. Its potential depends upon the user; a user can add the component to it according to need. The optical component layout can be controlled by an all-inclusive Graphical User Interface (GUI) there is a library of an active and passive component which has wavelength parameter. In opti-system software, there is advantageous of using parameter sweep during simulation. By parameter sweep, we can the check the effect of the certain device on output.

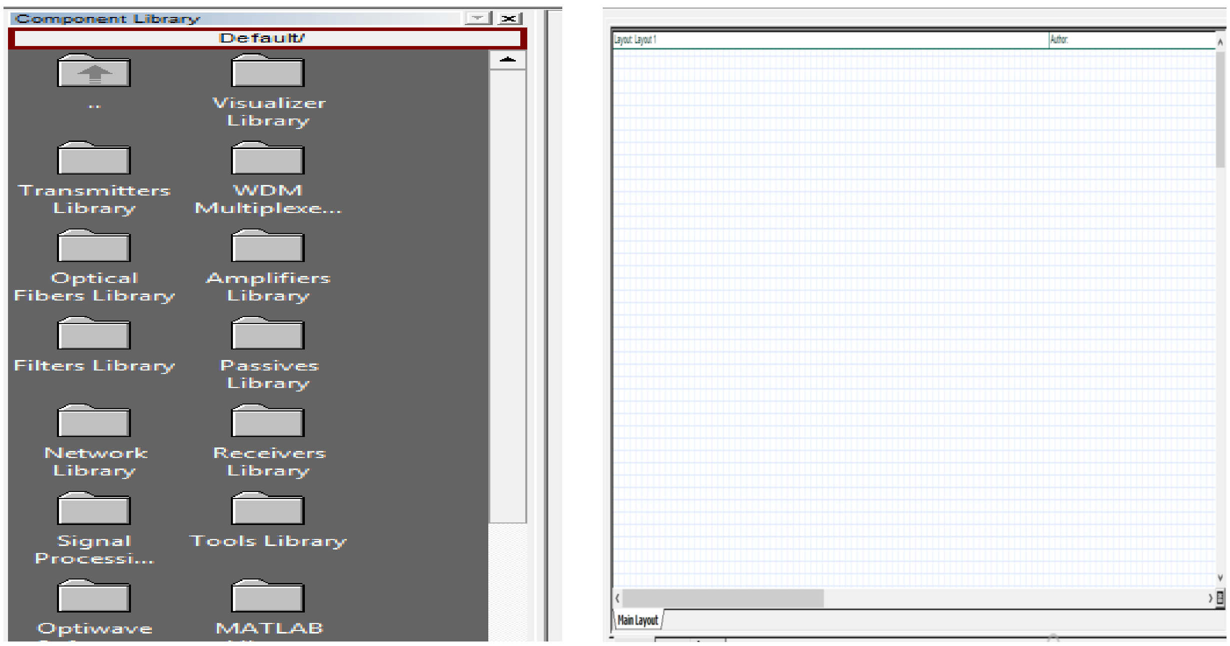


Figure 1.18 Component Library & Project Layout

Figure 1.18 is the view of component library and Project layout of optisystem7 software used of simulation. In project library there are electrical as well optical components present.

Chapter 2

Literature Review

In an optical communication system, incoming light is confined in the optical fiber to a very small region due to this increase in the power supply or even less amount of power produces nonlinearities in the optical fiber. There are many types of nonlinear effects in the optical fiber. Fiber nonlinearities have considerable effects in the optical system. There are various types of nonlinear effects inside a fiber line when light transmits over a distance. Mainly this is the case when very short pulses are used for transmission or on Optical Amplifier for amplification. SPM, CPM, and FPM are three types of nonlinear effects as given in XPM [5], SPM [3] and FWM [8]

The performance of 8-channel WDM system using dispersion compensation technique [7] is optimized. WDM link is optimized by comparing performance at three wavelength 980nm 1300nm and 1550 nm in single mode fiber. 15km DCF length, 105Km fiber length .9dBm power and EDFA gain of 19dBm is used with 3Gbps bit rate in a simulation. As compared to 980nm and 1300nm performance at 1550nm is better and 16.2516 Q-factor and Min BER 1.084e-059 is obtained.

Theoretical study of CPM presents in [5]. Cross-phase modulation induced crosstalk in a system which is described by system equation, in his study various types of optical fiber is used for simulation. The experimental result shows that nonlinearity increases as optical source power increases and no. of transmitted channel increases. SMF DCF, NZDF & NZDFS these four types of optical fiber react differentially .when they are sued in the same optical network. NZDFS & NZDF are same to each other to some extent and SMF &DCF are close to each other. Noise in XPM is different for different types of fiber.

Comparative effects CPM and SPM is can be seen in an optical fiber [6] Result are conducted by optisystem7 at 10Gbps bit rate and analyzed by eye diagram, q-factor. Two types of nonlinearities are compared. Nonlinear dispersion due to SPM effective when only one wavelength is used in WDM .Q-factor of 5.849 is achieved in 100 km fiber length at 193.1 THz frequency. In XPM 193.1THz & 192.4THz are used with 100 km fiber length 2.70798 * 10-7 BER is achieved. By conclusion for the single wavelength, SPM is better than XPM. Nonlinearities in Optical fiber damage the optical signal in WDM system by the effect of XPM & SPM [4].In this paper pump-probe experiment is analyzed in optic system. Channel spacing and XPM power transfer are done by drive formula as a result which limits the no of the channel in WDM system. Channel spaced at 300GHz have Q-Factor 6.8 and 4.05*10^-12 BER is optimized for 250 km length with pump power and probe power 0dBm and -10dBm respectively with 40GHz bit rate.

Nonlinear effects weaken the WDM performance in RoF system. Analyses are done without using any external amplifier. It is observed that effect of FWM nonlinearities becomes less when the power level is decreased and when the spacing between channels is decreased then FWM effect is decreased. It is recognized that FWM nonlinearities can be reduced in WDM system network [10].

Nonlinear fiber optics has a main job in designing of light wave system that has the high capacity [15]. Optical fiber performance is limited by nonlinear effects. The nonlinear effect is examined using the opti-system software. As a result, SPM sets high as power increases, which diminish the signal. At constant spacing between WDM channels XPM also rises with the rise in power but at less channel spacing there is a significant amount of XPM effect. Due to Four waves Mixing signal pulse is distorted. When in DWD spacing between channels is increased then side lobe side lobe power is reduced due to the reduction in FWM effect. When dispersion value is high FWM effects are reduced.

Wavelength conversion process is observed using four types of fiber [17] describes the process of wavelength conversion using the nonlinear property of fiber called four-wave mixing. Wavelength conversion used to route the wavelength to different request port. Wavelength is converted at 1.55um using four of fiber, SMF-28 Single mode fiber, positive dispersion non-zero dispersion shifted fiber(LEAF), Negative dispersion non-zero dispersion fiber(METRO), Dispersion compensation fiber. By using peak pump power and signal power 6.5W and 2.4mW respectively. As a result of the simulation, FWM-wavelength conversion occurs in the range of C-band. Out of four tested fiber DCF shown the good result of conversion when fiber length is varied from 2.2m to 22m. The nonlinear effect depends upon the length of the fiber because more the transmission length of optical fiber there is more interaction time for two wavelengths.

[18] Wavelength and optical time division multiplexing optical wavelength conversion is necessary. Nonlinearities in optical fiber and semiconductor optical can be used for this process. There are favorable of bit rate transparency, low chirp and no extinction ratio degradation in wavelength conversion process. Pump power and signal power are 0dBm and 2dBm respectively. The fiber length of 1 and 7 km is used for simulation By using opti-system 12.0 power of converted signal can be calculated. As a result, DCF Fiber has the advantageous over the other fiber because its effective area is smaller as compared to other and power of -40.4 dBm and -51dbm is obtained at 7km and 1km.

On gap work papers on Mach-Zander interferometer of 2x2 and 4x4 are also studied.

Chapter 3

Non-Linear Effects in Fiber

In linear optics a light wave work on an incoming molecule, which reverberate, by this vibration, there is ejection of its own light wave n this wave combine to the original beam of light. Example- if the input to the lens is red light then at the output of lens it is still red. Non-linear optics is advantageous in the optical fiber communication system. This allows the change in color of a beam of light to alter its shape in time and space in the communication system and be doing this many effects are born. Example-white light to the input of prism but output light contain combination of many colors

3.1 Non-linearity in fiber optical communication

In linear optical medium properties or fiber properties do not depend on the signal when the pulse is propagating in a linear fiber optics then the property of propagation is decided just by the medium property. In linear optics wave equation are used to find out the characteristics of a pulse.

The behavior of propagation of light in the nonlinear medium is described in non-linear fiber optical communication system. In nonlinear fiber optics, material properties are modified by the signal itself. In the nonlinear fiber optics refractive index of the material depend upon the intensity of light. Here refractive index increase with the intensity of light .whole pulse will not face same propagation properties because refractive index is different from the different place.

At center light intensity is high so refractive index is high but on either side, if core intensity of light is less so refractive index is less. In non-linear fiber optics propagation of pulse is not stable Means if the continuous pulse is transmitted through a fiber then any small perturbation break this continuous signal into small pulses.

The dielectric constant of a medium –when the electric field is imposed in the dielectric medium, there is induced polarization inside a material which is given by susceptibility of the medium and we consider only high order susceptibility in the polarization of the light.
In general, induced polarization in the material is[12].

$$P= \varepsilon_0 \{ \chi^{(1)}. \bar{E}+ \chi^{(2)}: \bar{E}\,\bar{E}+ \chi^{(3)}: \bar{E}\,\bar{E}\,\bar{E} + \ldots \quad (3.1)$$

here ε_0=free space permittivity

$\chi^{(1)}$, $\chi^{(2)}$, $\chi^{(3)}$ are 1st, 2nd and 3rd order susceptibility respectively.

$\chi^{(1)}. \bar{E}$ = dominant term contributes to dielectric constant

$\chi^{(2)}: \bar{E}\,\bar{E}$ =$\chi^{(2)}$ is very small for Sio_2

$\chi^{(3)}: \bar{E}\,\bar{E}\,\bar{E}$ = contribute to nonlinear effects

Third order susceptibility tells that refractive index is square of the electric field. Nonlinear effects s SPM, CPM, and FWM are all due to 3rd order nonlinearity
Now change in refractive index due to non-linearity is given in Eq (3.2)

$$n_2=\frac{3}{8n}\ \chi^{(3)} \ldots \quad (3.2)$$

For glass n_2=2.3*$10^{-22}m^2/v^2$

Figure of merits of nonlinear interaction (FOM)-

$$\eta= I * L_{eff} \ldots \quad (3.3)$$

Here I= intensity of light in watt/ m^2

L_{eff} = Interaction length in meters

3.1.1 Karr non-linearity- Change in refractive index is proportional to the square of applied electric field, pointing vector or power density. Or in short refractive index is proportional to power density inside a fiber this is called karr nonlinearity. So opposite to linear medium there is a change in wave equation in a nonlinear medium. Here nonlinear as well as dispersive both effects are presents. If the pulse width is larger than 10ns then the nonlinear effect is dominant. But if Pulse is between 10 fs to 10ns then both effects are present and pulse propagation is directed by the cumulative effects of both.

DWDM is slightly different from DWM in term of spacing between adjacent channels. In DWDM channel spacing is less as compare to WDM it is about 200GHz. By using DWDM on one side we have speed and increased capacity on other sides. But there is opposite effect of using DWDM is that Increased channel and increased capacity, channel spacing is reduced. By DWDM more users can be utilized by increasing power but on increasing power, there is interference between channels due to less channel spacing. To overcome losses due to linear effect is easy but losses due to nonlinearity are not so easy. Increase in power increase the nonlinearity.

3.2 Types of nonlinear effects

There are many types of nonlinear effects but stimulated ramen scattering (SRS), stimulated brilliant scattering (SBS), cross phase modulation (CBM), self-phase modulation (SPM), are the considerable nonlinear effects. But out of these all FWM (four wave mixing) is most effective and considerable and comes from the interference of at three or more wavelength.

The nonlinear effect comes into effects due to the dependency of refractive index on change on power across it. Change in refractive index is given in Eq. (3.4)

$$\Delta n = n_1 + n_2 \left(\frac{1}{effective\ area}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.4)}$$

here Δn= change in refractive index

n_1= linear refractive index

n_2=nonlinear refractive index

Following are three types of non-linear effects that depend on change in refractive index

3.2.1 Self-Phase Modulation (SPM)

Self-phase modulation is one the non-linear optical effect change in refractive index due to propagating signal. A pulse when traveling in an optical fiber, produce a change in refractive index of the optical fiber core due to the dependency of refractive index on power intensity i.e. optical Kerr effect. Frequency chirp is produced by self-phase modulation. This variation in refractive index gives birth to phase shift of pulse, by which there is a change in pulse frequency spectrum [9].

Self-phase modulation is self-induced phase shift comes while a pulse is propagating in optical fibers. An optical pulse having high intensity faces high refractive index but sides of the having low intensity faces less refractive index while it propagates through the fiber. The positive refractive index gradient is faced by leading edge and a negative refractive gradient is a face by trailing edge. Broadening of pulse spectrum is due to self –phase modulation but there is the change in pulse shape. Self-phase modulation has an important role in the generation of Soliton generation, compression of pulse and optical switching operation.

Figure 3-1Spectral Broadening Of Pulse

The nonlinear phase is proportional to the power of optical pulses. The chirp in output optical pulse is directly proportional to the derivative of the power of optical pulse. In above figure, frequency decreases on leading edge but there is an increase in frequency in trailing edge.

Application of Self-phase modulation- Optical generation of WDM channel, optical switching, Passive optical network mode locking.

A technique to reduce Self-phase modulation- Optical power can be decreased to mitigate self-phase modulation effect but on decreasing, power level noise is increased. Proper dispersion management can also be used to mitigate the self-phase modulation.

3.2.2. Cross-phase modulation (CPM)-

It is nonlinear effect occur in optical fiber when of one wavelength is affected by the phase of another wavelength through optical Kerr effect. Cross-phase modulation occurs due to change in refractive index seen by the optical pulse is proportional to the power intensity of that pulse and other propagating pulses.

In cross phase modulation at one wavelength power changing in one pulse changes the phase of other pulses. Asymmetrical broadening off spectral shape and change in pulse shape occur. When wavelength spacing is increased, when interaction interval of two pulses is less and XPM effect is very small. Through XPM pulse retiming and compression of the pulse can be done. Information can be added to light by changing the phase and beam of one light with respect to other light through interaction in a proper non- linear medium [9]

By direct modulation and intensity modulation, XPM effect is visible in DWDM. If there are two signals propagating in DWDM then with the help of 2nd signal 1st signal is phase modulated then phase modulation is converted to power variation by dispersion. Walk of between co-propagating channels depends upon dispersion. If dispersion is less then walk off is more and XPM effect is more and if dispersion value is more then walk is less or respectively XPM effect is less. So there must be a small amount of dispersion in a system.

Advantages of cross-phase modulation –Nonlinear pulse compression, Wavelength conversion in WDM channels, Optical switching (switching time 1ps)

Disadvantages of cross phase modulation- Produce amplitude and timing jitter and cross-talks due to inter-channel interference.

3.2.3. Four-wave mixing (FWM)

Intermodulation process in the non-linear optical system is called FWM. In FWM interaction among at least three wavelengths produce new wavelengths. The concept of Electric system's third order intercepts point and intermodulation distortion is similar to FWM. The energy of incoming light in term of photons has converted.

Oscillation and Parametric Amplification in four-wave mixing are one if the effects which comes in four-wave mixing. Parametric oscillation is done by input of a light signal at a λ1 wavelength to the fiber and non-linear gain produce at λ2 wavelengths. Here λ1 & λ2 are two different wavelengths. This process is utilized in amplification of signal, i.e. signal produce at λ2 without given signal at this wavelength [10].

3.2.3 Raman scattering-

Raman scattering is of two types Spontaneous Raman scattering & Stimulated Raman scattering. Spontaneous Raman scattering is a random process in which light photons are scattered by base material. On contrary to this Stimulated Raman scattering produced when silica molecules vibrate and scatter the light transmission path. Silica has an amorphous nature which changes vibration into the band. At 13THz Raman gain is maxima and gain spectrum is up to 40THz. This Stimulated Raman scattering is one of the non-linear effects in optical fiber given by non-linear susceptibility of 3rd order i.e. χ^3[6].

$$P_{th}(SRS) \approx \frac{16A_{eff}}{g_B L_{eff}} \ldots\ldots(3.5)$$

3.2.4 Brillouin Scattering-

When light is scattered from acoustic waves this is called Stimulated Brillouin Scattering. For Stimulate Raman scattering input power should be more than a threshold level.

Approximately 5mW power is the low threshold power for long fibers. Most of the power is reflected when input power crosses the threshold level.

This scattering is performed by Bragg diffraction. Through electrostriction density variation is produced, by this index grating is produces which gives Stokes through Bragg Grating. Power threshold value is given in Eq-(3.6)

$$P_{th}(SBS) \approx \frac{21A_{eff}}{g_B L_{eff}} \ldots\ldots (3.6)$$

g_B : Brillouin gain coefficient = $5 * 10^{-11}$m/w

$L_{eff} A_{eff}$: Effective length and effective area of fiber

Table 1 Comparison of SPM, CPM and FWM

Non-linear → phenomenon Characteristics ↓	SPM	CPM	FWM
Origin	Nonlinear susceptibility χ^3	Nonlinear susceptibility χ^3	Nonlinear susceptibility χ^3
Effect of χ^3	Phase shift due to own pulse	Phase shift due to co-propagating signal	New waves are generated
Shape of pulse broadening	Symmetrical	Maybe symmetrical	—
Energy transfer between medium and optical pulse	No	No	No
Bit rate	Dependent	Dependent	Dependent

Table 1 Shows the Comparison of SPM, CPM and FWM in form of their origin, shape, bit rate pattern and effect of susceptibility. In Self-Phase modulation phase shift is due to own pulse only but in CPM phase shift is due to co-propagating signal also. In FWM new components are generated.

Chapter 4
Four Wave Mixing

4.1 Four Wave Mixing

FWM comes in effect by the non-linear response of material's bond electron of an applied filled (optical field). Polarization-induced in this medium has both terms i.e. linear as well as nonlinear. Susceptibilities order tells about the magnitude of linear and non-linear terms. The phenomenon of FWM is due to 3rd order susceptibility. Study on Four-wave mixing in the optical fiber has to be studied in detailed because this effect is helpful in the origin of the new wavelength at the output, irrespective of different wavelengths at the input.

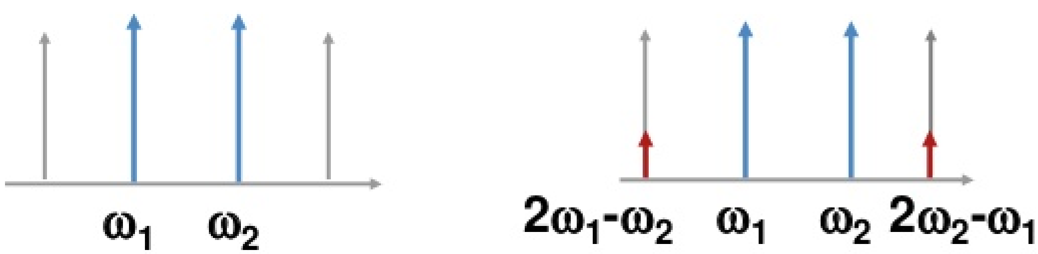


Figure 4.1 FWM Component on Mixing

Here w_1 and w_2 are input frequencies

$2w_1 - w_2$ & $2w_2 - w_1$ are the new sideband frequencies at the output of fiber due to FWM effect and these due to mixing input frequencies. If there are N wavelengths at the input of fiber then no of output wavelength due to mixing of input wavelength is M as given in Eq(4.1) where N=no of input channels

$$M=\frac{N^2}{2}(N-1) \qquad (4.1)$$

4.2 Methods to reduce Four-wave mixing-

a) Increasing channel spacing- Four-wave mixing becomes effective only when the spacing between consecutive channels is very less. So when the spacing between adjacent channels is increased frequency do not overlap or interact with each other within in band so the effect of FWM becomes less because this increases the mismatching of group velocity between the channels. Increased channel spacing has a drawback of increasing bandwidth.

b) Uneven channel spacing- by unequal channel spacing bandwidth cannot increase much and FWM effect also reduced Due to unequal channel spacing frequency do not overlap. This method needs exact calculation of the position of channels at the input port.

c) Minimum launching power-

4.3 Effect of four-wave mixing WDM-

FWM is good or bad: It depends on to use this affects. FWM results in inter-channel crosstalk in WDM system. It generates extra noise at another wavelength which degrades the performance of the system. Contrary to this four-wave mixing can be used for Optical phase conjugation Parametric Amplification, demultiplexing of OTDM channels, supercontinuum and wavelength conversion of WDM channels.

4.4 Application of Four-wave mixing

There is much application of four-wave mixing but the following are some important application in the optical fiber.

4.4.1 Parametric Amplification in FWM-

Weak signals are amplified using Four-wave mixing. In four-wave mixing pump power is transferred to signal. Peak gain Gp=$\frac{1}{4}\exp(2\gamma P_0 L)$. P_0= input power

Gp (peak gain) can be increased to 20Db for P_0 = 0.5W and Length of 1 km. In Parametric amplification using pump power gain can be taken at any wavelength. At bandwidth of greater 40 nm two pump power can also be used to obtain gain of 30-40 dB. Parameter amplifier is used for ultra-fast signal processing.

4.4.2 Squeezing-

In general is an amplification of signal and idle wave is called squeezing. At idle frequency photons with random frequencies are generated by spontaneous emission Squeezing is a process in four-wave mixing which is used to minimize the quantum noise. Here for noise fluctuation some type of states produced in electromagnetic field which contains noise level below the quantum noise level for some specific range of frequencies. For squeezing purpose FWM is used because in FWM fiber nonlinearities are used to couple the frequency and noise component at the signal.

4.4.3 Optical Phase Conjugation-

The optical fiber communication system has many non-linear effects one of them is FWM. Four-wave mixing is used as an application in Optical Phase Conjugation. During parametric amplification, FWM generates an idle wave. Due to spectral inversion, this idle wave has complex conjugate phase to that of the signal field. Phase conjugation can be used in place of the parametric amplifier for dispersion management.

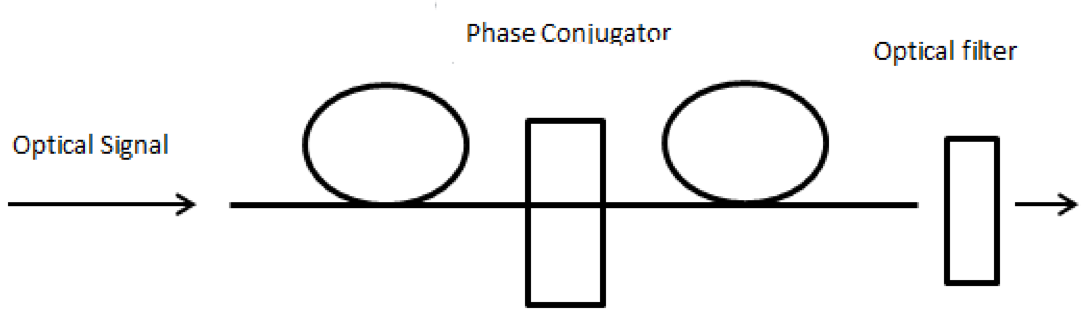


Figure 4.2 Optical Phase Conjugation

4.4.4 Wavelength Conversion-

Four-wave mixing is a process of transferring the data to a wavelength which is different from the input wavelength. At input side along with signal CW pump laser is used to modulate the signal before transmission through the fiber. Wavelength conversion is achieved at half of distance to final destination of transmission. So wavelength conversion is the process of transferring the data from an idle signal to new wavelength.

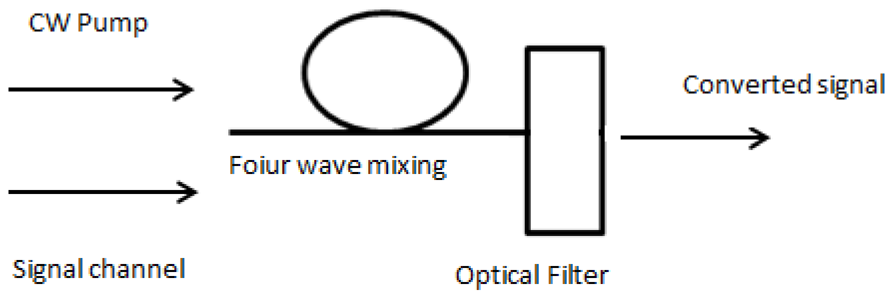


Figure 4.3 Wavelength Conversion.

4.4.5 Super-continuum Generation –

In optical fiber communication system when the effects of many nonlinear processes is working on a pump beam and broaden the pump signal is called super-continuum. When Four-wave mixing effects are combined with self-phase modulation, cross-phase modulation and stimulated Raman scattering effect, Pulse spectrum is super broadened which extend up to>200nm. Use of microstructure optical fiber is an example of Super-Continuum. Optical Coherence tomography, carrier- envelope phase locking, and telecommunication are main application of four- wave mixing.

As a conclusion, optical fiber has different types of non-linear effects. To take the advantages of nonlinear effects different types of fiber has been made. Nonlinear effects, affect the system performance negatively. But by using proper design structure advantage of these effects can be taken in many ways and above explained application are an example of this. Nonlinear effects of fiber are used in Optical switching, Broad-band application, Demultiplexing and Soliton formation.

Chapter 5

Simulated Result and Discussion

In this chapter, DWDM network is investigated for different parameters and results are obtained at different parameter. Effects of Cross-phase modulation and four-wave mixing are seen in the design. The different parameter is studied for the reduction of four-wave mixing effect in DWDM. Eight channel DWDM design is used. The data rate, channel spacing, the number of channels, dispersion value and fiber length are investigated for the optimized result. The decrease in input power, decrease the channel spacing, increase the area, non-zero dispersion value and increased fiber length are the methods to reduce the four-wave mixing in DWDM.

Designing of DWDM network and simulation is performed in Opti-system software and results are seen by BER analyzer. Eye diagram, optical and time domain visualizer, power is checked by power meter both in the electrical and optical domain.

5.1 Design introduction-

Transmitting signal in the form of pulses from source to destination in an optical fiber is called fiber optic communication system. WDM is processed in which multiple channels are transmitted over a single piece of fiber but wavelength used for the individual is different. DWDM is varied from WDM in a way that in a DWDM no. of the wavelength used for multiplexing are more than WDM. In DWDM, dense wavelength divisional multiplexing, multiple channels are combined or multiplexed having the different wavelength in order to full the demand of increasing number of the user. In DWDM channels spacing is varied depends upon requirement and number and no of user and nonlinearity effects. But is spacing is very less and the number of users is more then there is unwanted result in the output and network doesn’t fulfill the requirements. There are many nonlinear effects in the system outputs which are not required and deteriorate the result. That non-linearity are SPM (self-phase modulation), CPM (cross phase modulation) FWM (four wave mixing). These effects are due to the interaction between the wavelengths those are traveling inside the same fiber. Self-phase modulation modulates the phase of own wavelength. Cross-phase modulation modulates the phase of corresponding wavelength and four-wave mixing power produced at the receiver in fiber end by the interaction of wavelengths.

5.2 FWM effects at the output of fiber-

The FWM effects depend upon many factors as the input power is increased then the effect is also increased. When new frequencies are produced and they may coincide with the original frequency, from this there is crosstalk between transmitting signals in the optical fiber. This crosstalk becomes very serious input power is very high and channels spacing is very less.

Table 2 Simulation parameters of FWM

Reference wavelength	15550nm
Bit rate	2.5 Gbps
CW laser(source1)	194.67THz
CW laser (source2)	194.60Thz
SMF1	33.33Km
SMF2	200Km
Attenuation constant	0.2dB/km
Dispersion	16ps/nm^2/k

Above table shows the parameters used for simulation of FWM validation.

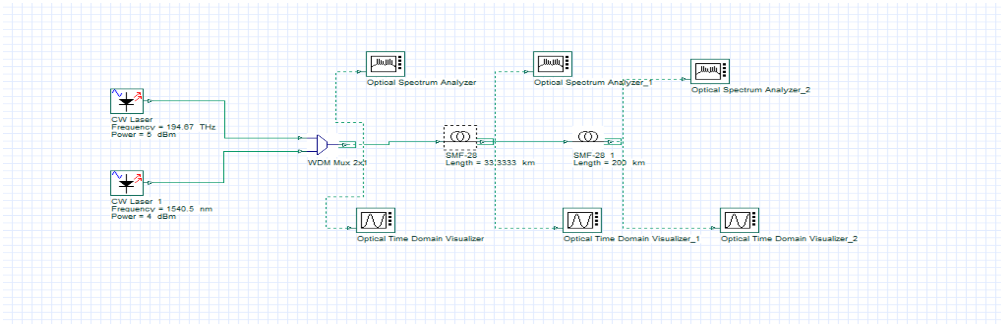


Figure 5.1 FWM Validation

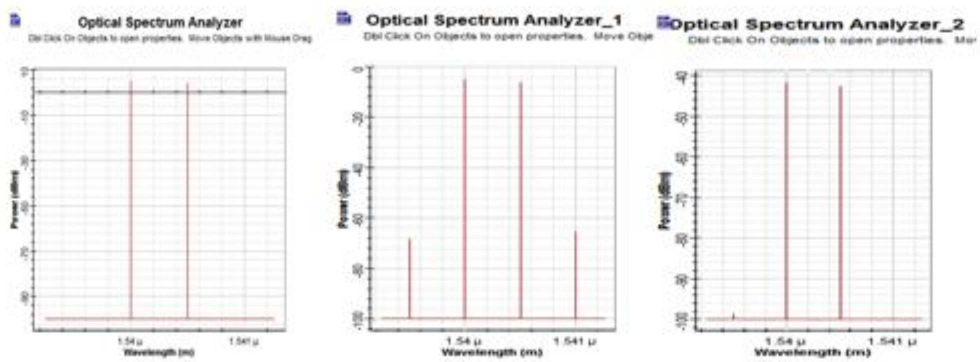


Figure 5.2 Optical Spectrum Analyzer for FWM validation.

Figure 5.2 shows the results of opti-system design for Validation of Four Wave Mixing Design as shown in figure 4.1. In this design, two CW laser is used as source signal with wavelength 1540nm and 1540.5nm and power level is 5dBm and 4dBm respectively. Two signals are multiplexed using WDM multiplexer. Then SMF-28 fiber is used as a transmission medium with 33.33km length, 0.2dB/km attenuation and 16ps/nm/k dispersion. After 33.33 km fiber result is seen through optical spectrum analyzer_1. With two transmitting wavelength there are some extra wavelength at this length these are due nonlinear effects but as length of fiber increases to 200km, FWM effects are decreases as shown in spectrum analyzer_2

5.3 Designs and simulation results of DWDM

5.3.1 Basic model-

This is the setup for the optical communication system. Here on adding optical fiber for communication nonlinearities i.e. FWM, SPM and XPM comes in the system. For long distance communication amplifier are used to boost the weak electrical signal so that output signal must be strong to handle noise. Without using amplifier output signal is noisy and distorted. Amplifier used in optical fiber communication may be preamplifier, post amplifier, and in-line amplifier

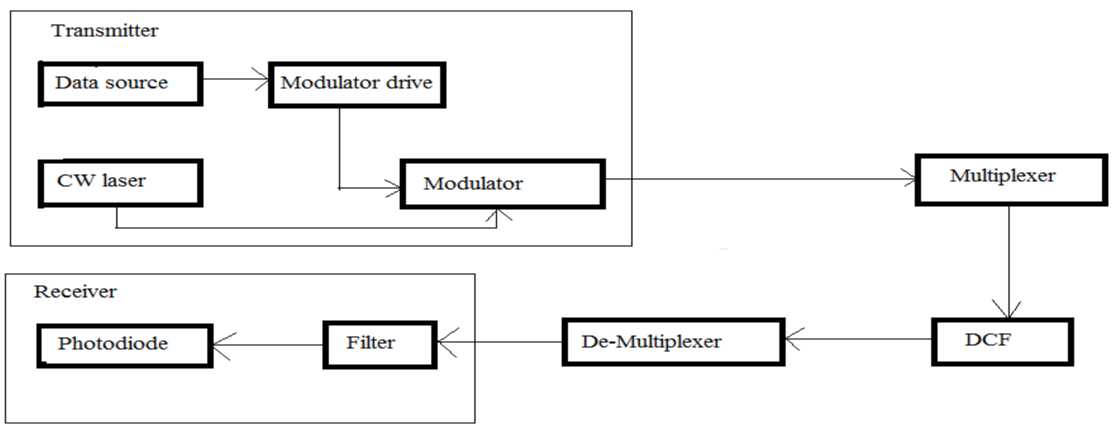


Figure 5.3 Basic Model of FWM

In transmitter section there is Data source - pseudorandom bit sequence generator, modulator drive –NRZ bit sequence generator, Source-CW laser, and Mach-Zander as a modulator. The multiplexer is used to combine all transmitted signals from the source. For transmission of multiplexed signal up to the long distance, the signal is amplified and sends in a nonlinear fiber line. In between the fiber, DCF is used to compensate dispersion effect. The nonlinear fiber produced nonlinear effects in transmitted signal called nonlinearity. The demultiplexer is used to separate the entire signal so that it can be sent to individual destination. Photodiode and low pass filter is used in receiver side of model

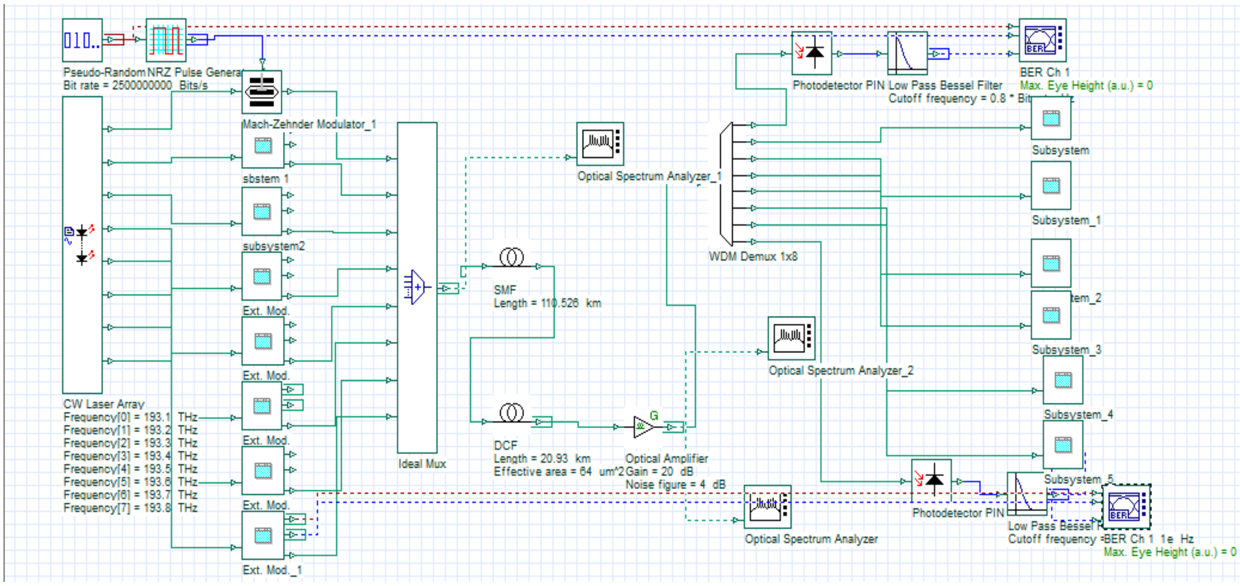


Figure 5.4 FWM Design in Opti-System

5.3.2 Simulation setup-

Above figure shows a WDM system having been eight channels multiplexed. Fig. 4.2 shows system setup for eight-channel at 2.5Gbps. Pseudo-random bits are generated by PRBS generator at 2.5Gbps.These bits are given to NRZ pulse generator and it generates NRZ sequence. In optical time domain multiplexing networks, return to zero (RZ) format is used because instead of dispersion effects, it has tolerance to fiber nonlinearities and for WDM networks non-linear to zero is preferred for its easy way of implementation, having tolerance to timing jitter tolerance and comparatively high spectral efficiency. To create carrier signal Transmitter have 8 CW (continuous wave) semiconductor laser sources. These light sources are individually modulated by eight Mach-Zander modulators.

Modulated signals from eight Mach-Zehnder modulators are multiplexed in a multiplexer. Post amplifier is used to recover the original signal that gets distorted over the optical fiber. In simulation parameter dispersion, nonlinear effects and dispersion are activated. Phase mismatching is introduced in the signal by DCF (Dispersion compensation fiber) which is used to compensate the dispersion effect in the fiber. The preamplifier has to be used prior to a demultiplexer. Demultiplexer splits the signal into eight signals. Then by using photodiode optical signal is converted back to electrical signal. Then the signal is passed through a low-pass Bessel filter is used for flat phase and group delay. Then for result comparison, BER and Q-factor are used.

Simulation Parameter-

Table 3 parameters of FWM Design in DWDM

Sr. No	Parameters	Values
1.	Reference wavelength	1550nm
2.	Bit rate	205Gbps
3.	No Of Channels	8
4.	Pulse Generator	NRZ
5.	Modulator	MZI
6.	Fiber	SMF(110.256Km)
7.	Compensating Fiber	DCF(20.93Km)
8	Optical amplifier	Gain 20dB Noise figure-4dB
9	Photo-detector	PIN
10	Filter	Low pass bessel

Table 3 shows the parameters used for DWDM design for FWM. Reference wavelength used is 1550nm.

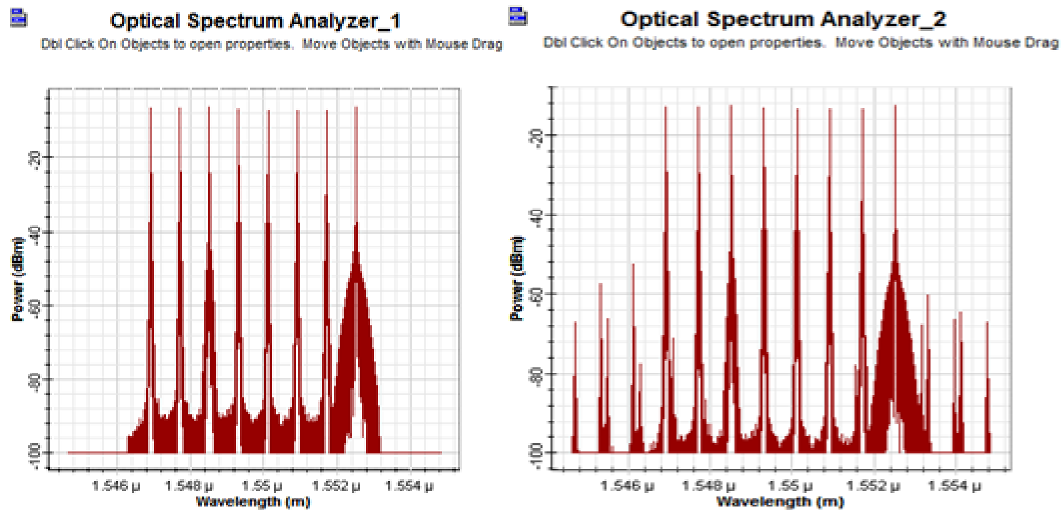


Figure 5.5 Outputs of spectrum analyzer for 110.256km fiber length

Figure 5.5 is output of spectrum analyzer 1st figure shows the output after multiplexer. 2nd figure shows the output after travelling 110.256 km length of fiber. It is clear that original input pulses having a power level of -12.9dB and power of pulse those comes from FWM effects are approx. 67dB. It is seen that at 1.546um and 1.554um there is new frequency component by Four-wave mixing effects.

5.3.3 Analysis of Four-wave mixing

A) Effect of Input Power on Four-Wave Mixing-

When the power of input source is changed to other value then there is the change in four-wave mixing power. When input power is increased then Four-wave mixing power is also increased. Following graph shows that at -15dBm four-wave mixing power is -85dBm and at +15dBm power level is increased to -5 dBm.

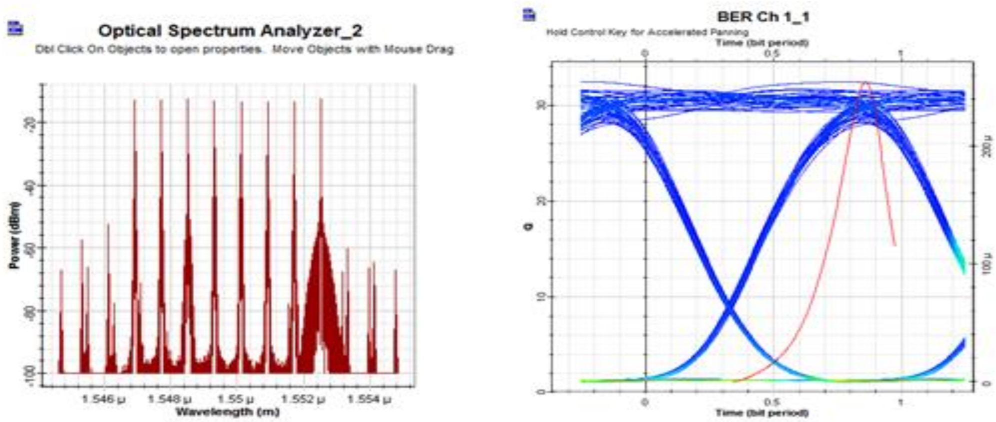


Figure 5.6 Spectrum analyzer and Eye diagram for 0dBm input power.

The optical spectrum analyzer and Eye diagram are shown in figure 5.6 for 0dBm power level. Signal power and Noise power level at different frequency component is shown in Table 5.1.Input power is varied from -15dBm to +15dBm changes in four wave mixing component are observed.

Table 4 Optical Signal to Noise Ratio with 0 dBm power

Frequency(THz)	Signal power(dBm)	Noise power(dBm)	OSNR(dB)
193.1	-9.5625819	-33.978119	24.415537
193.2	-9.4892	-33.975308	24.486108
193.3	-9.5425918	-33.972499	24.429907
193.4	-9.5076877	-33.969692	24.462004
193.5	-9.5535278	-33969692	24.416164
193.6	-9.5689546	-33.966887	24.397932
193.7	-9.461799	-33.964084	24.467904
193.8	-9.5555293	-33.961282	24.405753

Table 4 shows the optical signal to noise ratio when input power is 0 dbm

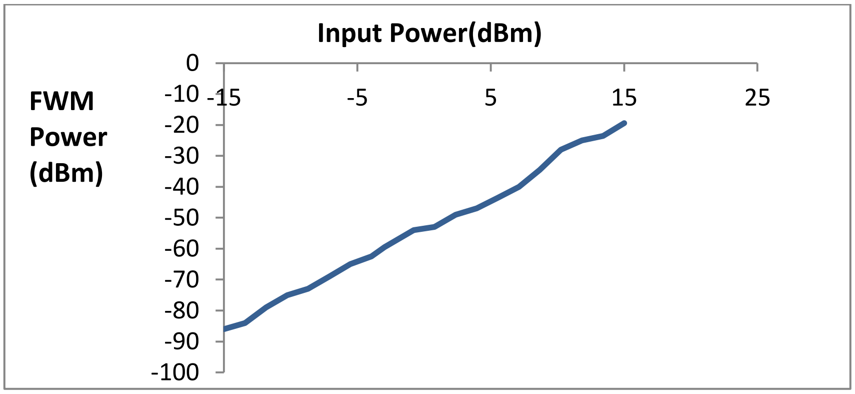


Figure 5.7 Variation of FWM with change in input power

Figure5.7 shows the effect of input power on Four-wave mixing component. It is observed that as input power is increased four wave mixing component is increased. At -15dBm, input power is -80dBm and at +15dBm FWM power is -20dBm.

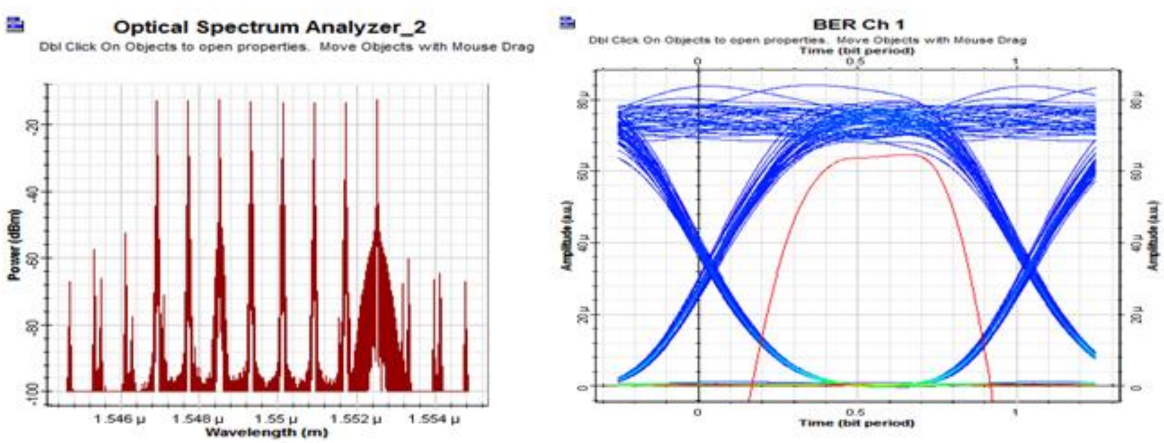


Figure 5.8 Optical Spectrum and eye diagram with -5dBm input power.

Figure5.8 shows the optical spectrum and eye diagram when input power is -5dBm.
It is shown that FWM components are decreases as power is decreased from 0 to -5dBm.

Table 5 Optical Signal to noise ratio with -5dBm power.

This is the table of Optical signal to noise ratio when power is -5dBm

In following table power of signal as well as noise component is tabulated .

Frequency (THz)	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
193.1	-14.5604	-33.9781	19.41771
193.2	-14.4904	-33.9753	19.48494
193.3	-14.5646	-33.9725	19.40789
193.4	-14.4795	-33.9697	19.49019
193.5	-14.5626	-33.9697	19.40709
193.6	-14.5685	-33.9669	19.39835
193.7	-14.4845	-33.9641	19.47962
193.8	-14.5666	-33.9613	19.39466

B) Effect of fiber length on Four-wave mixing-

When a signal with wavelength travels inside a fiber and at the end of fiber there are some extra wavelengths which are produced due to Four-Wave Mixing. These component properties depend upon the length of the fiber. When fiber length is small then these effects are more but when the fiber is increased then the power of this induced component is decreased.

In figure 5.9 variation of four wave mixing component with respect to length of fiber is shown .FWM decreases as fiber length of fiber is decreases.

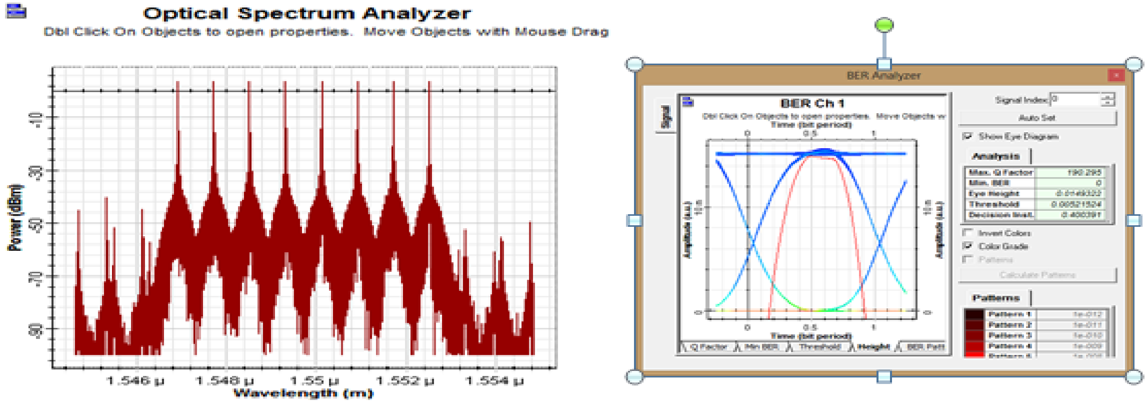


Figure 5.9 Four-Wave Mixing component after 20Km fiber length.

As shown in the 5.9 when fiber length is 20km then FWM power is about -40dBm but as fiber length is increased to 110km FWM power reduces to -80dBm and gain decreases as the length of fiber is increased.

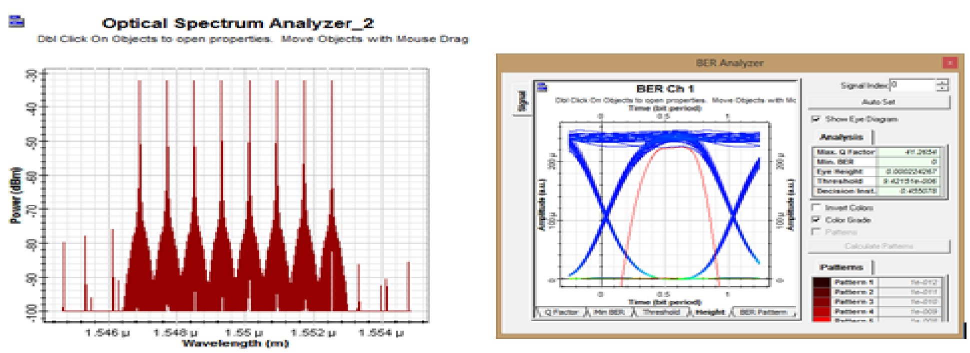


Figure 5.10 FWM Component at 110km Fiber Length.

Variation of four-wave mixing component with a change in fiber length is shown in figure 5.10. it is observed that as transmission length is increased intensity of four-wave mixing component is decreased in 5.11

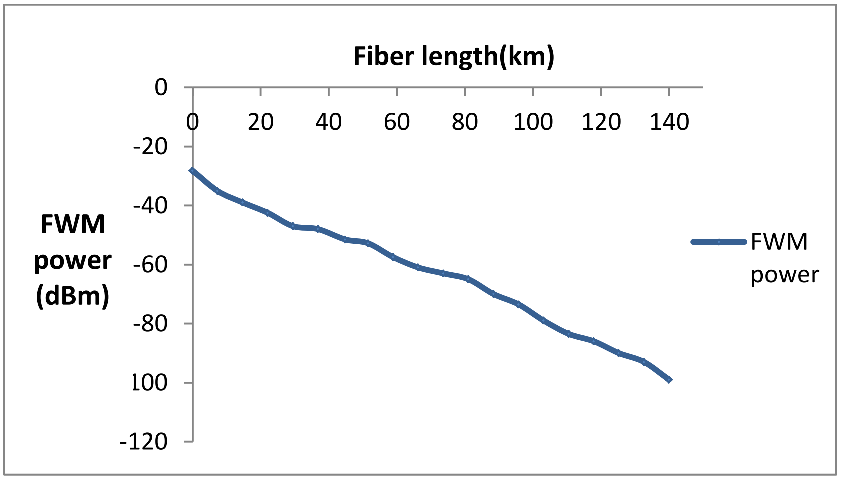


Figure 5.11 Variation of FWM Power with Fiber Length

C) Core size of optical fiber

As we know that on effective are is inversely proportional to input power so, on increasing the effective area of fiber four-wave mixing power is decreased. The following figure shows the four-wave mixing power decreases with the effective area of the fiber. When core size is varied but other valued are constant there is a reduction in FWM. When effective area increased, intensity inside fiber also decreases.

D) Effect of less input power and large fiber length-

When fiber length is increased but input power is decreased Four-wave mixing power is reduced.

5.4 Application of four-wave mixing-

Four-wave mixing has many applications in a different domain and some of those are a combination of optical phase, optical amplification based on nonlinearity of parametric and pump wave. Frequency comb generation resonator. Four-wave mixing based oscillator and amplifier use non-linearity of the third order, as a comparison to mostly parameter oscillators that uses the nonlinearity of 2^{nd} order. Two most important are Four-wave mixing are wavelength conversion & squeezing.

The Wavelength conversion application of four-wave mixing is described in this thesis and result are stimulated as follow-

5.4.1 Wavelength conversion in Four-Wave mixing-

Wavelength conversion is the process of transmission of data or information from one wavelength to other but there is no change in data or information. The conversion of wavelength is in an optical network is the important part of Four Wave Mixing because wavelength which is at the input is allocated to some other channel which places on an outgoing path so there is need of wavelength conversion. It is key components of transmission upcoming optical networks. One of the important things is that here only transmission wavelength is changed but transmitting data is same.

Wavelength converter types

All optic wavelength converter and an Electro-Optic wavelength converter. Working on Electro-optic wavelength converter is same as regenerator or repeaters. They give a copy of input of signal by converting an optical signal into an electrical signal and then by using this converted signal transmitter is operated to produce an optical signal of new wavelength.

In an optical network where the wavelength is routed from one port to other, sometimes wavelength blocking becomes a drawback. This drawback is overcome by wavelength conversion process which is used as an important parameter in the optical network, it provides better flexibility and right allocation of wavelength. If wavelength conversion is performed in the all-optical domain as compared to optical to electrical and then to optical conversion is good for bit rate problem. Current fundamental limit of the electrical system is 40Gbps [18].

Based on nonlinearity effect in semiconductor, optical amplifier, and crystal there are several approaches for wavelength conversion all in the optical domain. Among all other

nonlinearity, nonlinear effects in the optical fiber having the low noise characteristics very less response time of femtosecond, low insertion loss and extinction ratio is non-degraded. So for wavelength conversion using optical fiber, there are needs of suitable optical fiber for the better result. There are many types of fiber which are used in wavelength conversion process like DCF (Dispersion compensation fiber), SMF-28 single mode fiber, positive dispersion non-zero dispersion shifted fiber and negative dispersion shifted fiber.
The nonlinear effect used in wavelength conversion is FWM, SPM and XPM all comes from Kerr effects. Among all above four-wave mixing effect is better to use because of its translucent modulation format. The effect which is produced by nonlinearity n strengthen by high optical power are impacted by properties of optical fiber like effective cross-sectional area and transmission length.

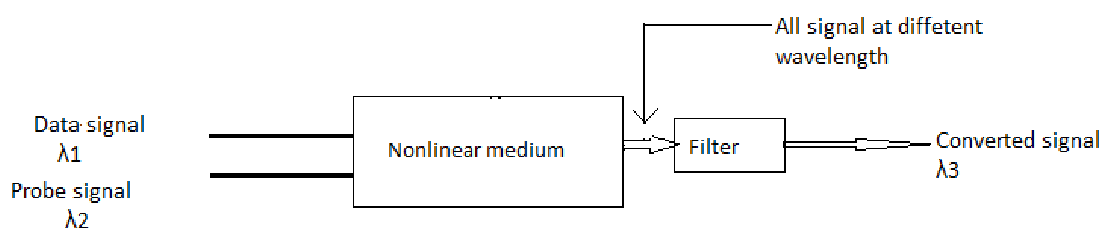


Figure 5-12Wavelength conversion by nonlinear effect four-wave mixing.

Above figure describes that data signal and pump signal are combined in the multiplexer and then given to nonlinear medium fiber, at output port signal comes at new wavelengths with the help of one of the suitable filter.
Conversion efficiency of wavelength converted by Four-wave mixing is given as

$$\eta = 10 log_{10} \frac{power\ at\ output\ port}{power\ at\ input\ port} = 10 log_{10} \frac{\lambda_{output\ signal}}{\lambda_{probe\ signal}}$$

There is phase mismatch between the different waves traveling inside the optical fiber having different group velocity. All phase mismatched term are being canceled. They are not considered because their contribution is very little. Only the last term of nonlinear polarization gives the four-wave mixing phenomenon.

As obtained from simulation four-wave mixing nonlinear effects depend upon the length the optical fiber because when the length is more interaction length is also more so more nonlinear effect. So it is stated the performance of four types of optical fiber which are used in this design cover entire C-band but conversion occurs only in given length of the fiber.

5.4.2 Wavelength conversion design-

Four-wave mixing can be used an important application for new wavelengths. The numerical simulation design which is designed in optisytem7 is shown below in Figure 4.14.

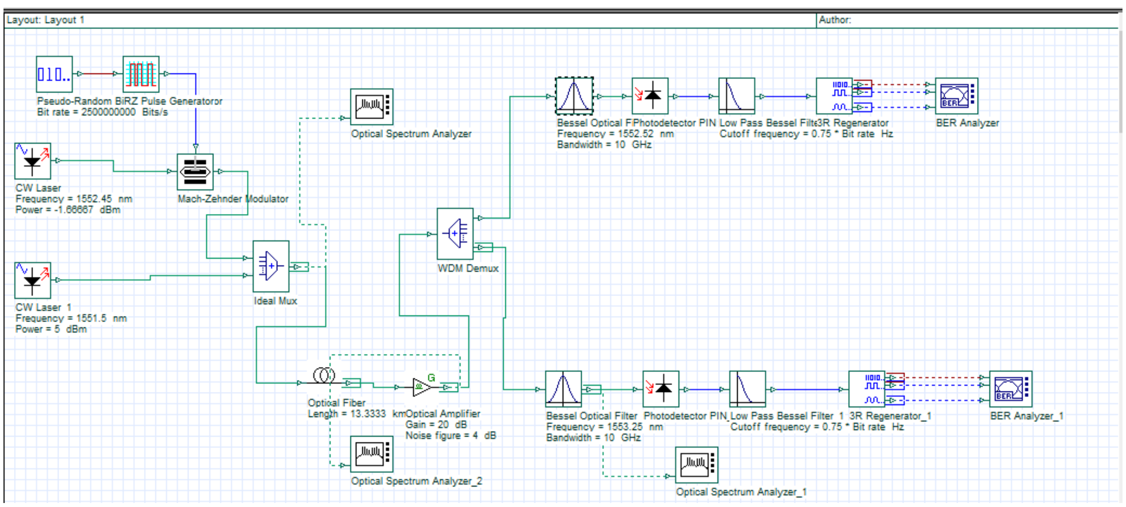
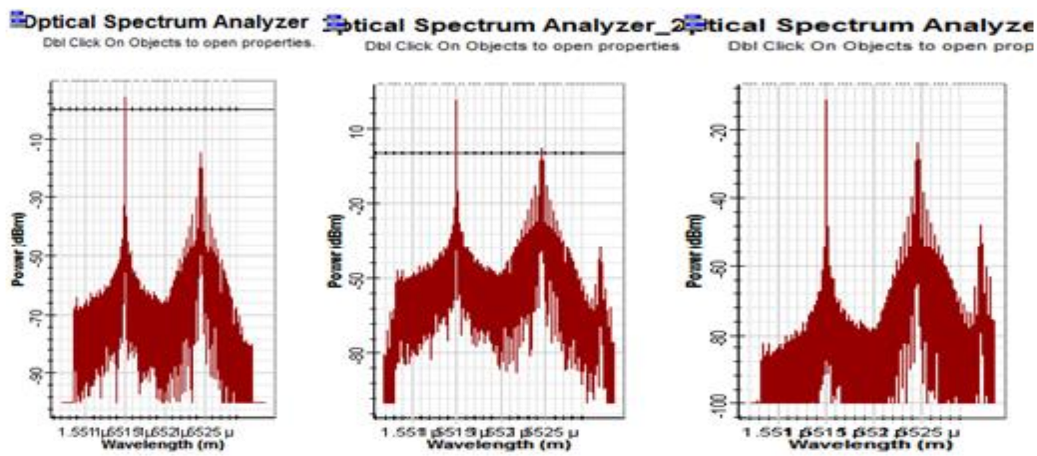


Figure 5.13 FWM as A wavelength converter

One pump signal with wavelength 1552.45nm and data signal with 1551.5nm wavelength is used. Three type of fiber is used for this purpose- SMF-28, DSF fiber and NZ-DSF (Negative dispersion shifted fiber). Pump signal is modulated using MachZehnder modulator. After optical fiber optical amplifier is used with 20 dB gain and 4dB noise figure. After that demultiplexer is used to separate the signal or to receives the signal at the separate wavelength. Bessel low pass filter is used which gives flat group and phase delay.

Bessel filter maintains the shape of the incoming wave. We can also use the Gaussian filter in place of Bessel filter.

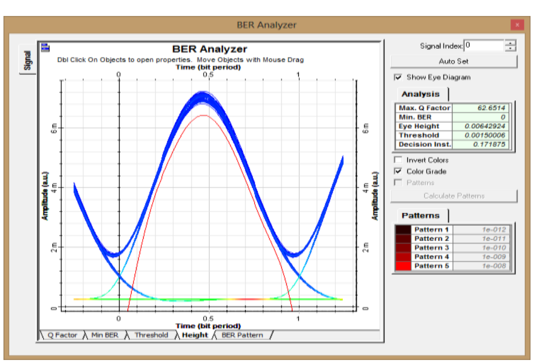
At receiver section, PIN photodetector is used at after that low pass filter. The eye diagram is observed by BER analyzer for Q-factor and Min BER. Generation of new frequency is seen by an optical spectrum analyzer.



5.14 FWM component at 13.33km fiber length.

Up-conversion- Data signal is at 1551.5nm and probe signal is at 1552.4nm is coming from two CW laser. Due to four-wave mixing new signal generated at 1553.1nm. The signal is Up-converted.

Down-conversion-- Data signal is at 1551.5nm and probe signal is at 1552.4nm is coming from two CW laser. Due to four-wave mixing new signal generated at 1550.7nm. The signal is Down-converted.



Eye diagram of wavelength conversion is Shown in 5.15 with Q-Factor 62.65.

Figure 5.15 Eye diagram of up converted signal

Table 6 Variable parameter of Four-wave mixing

Sr. No.	**Depending parameter**	**Effect of four wave mixing**.
1	Increases in Source power or Input power	FWM Increases
2	Increases in Transmission length	FWM Decreases
3	Increases Effective area of fiber	FWM Decreases
4.	Increase In no of channel	FWM Increases
5.	Increases in Dispersion	FWM Decreases

Table 6 gives the variable parameter of FWM component. FWM component increases with increase in source power or input power. As transmission increases then FWM component goes on decreasing. If there are zero dispersion then FWM component or other non-linear component are more so there must be some amount of dispersion in optical fiber.

Chapter 6

Conclusion

In this dissertation, Wavelength conversion using the Fiber Nonlinear effect in an optical - communication system is purposed. Nonlinear effects such as SPM, CPM, and FWM are discussed. These effects degrade the system performance. SPM effect is less if per channel input power is less. CPM broadened the pulse because the phase of each signal is changed by the presence of another signal. SPM & CFM Effect is seen when two wave travels at different speeds as they propagate inside the fiber with different velocity they essentially slide each other. During pulse interaction, pulse power is transferred and this is the process of cross-phase modulation. During CPM, SPM vanishes, because they are not inter-racting each other this is a walk-off phenomenon. The difference between SPM and CPM is that in CPM nonlinear phase is nonlinear modulated by additional channels also.

FWM has drastic effects in WDM system, this effect use dispersion shifted fiber. If dispersion is zero then four wave mixing effects are more so some amount of dispersion must be there in fiber. If dispersion is large, then velocities of two channels are different then walk of time is reduced and nonlinear interaction is very small. That is why in WDM system non-zero dispersion shifted fiber is normally used.

Although nonlinear effects deteriorate the performance of the system by proper design network and suitable parameters values there are much application of nonlinear effects. In pulse compression and solitons, SPM is used. In optical switching, CPM effect is used. FWM is used in wavelength conversion, Optical Phase Conjugation and in wavelength conversion.

In this dissertation, four wave mixing effect is shown by designing the WDM network in opti-system software. Reference wavelength of 1550nm is used in the design with attenuation of 0.2dB/km and 16ps/nm/km of dispersion. Results are calculated through an optical spectrum analyzer and BER analyzer. Sweep operation is applied on Length of the optical fiber, channel spacing, input power bit rate and no of channels are varied and effect is noted. Four-wave mixing effects are increased by increasing the input power, increasing the number of channels and decreasing length of the fiber. Four-wave mixing effects are decreased by decreasing the decreasing the channel spacing and effective core area. From simulation results, it is observed that nonlinear effect of fiber is used in wavelength conversion (Up-conversion and down conversion) using a suitable filter.

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