

Comparative Performance Analysis of FWM Effect in DWDM System

Dissertation submitted in the partial fulfillment of requirements for the award of degree

of

Master of Engineering

In

Electronics and Communication Engineering

Submitted by

PRIYANKA RANI

801461020

Under guidance of

Dr. Hardeep Singh

Assistant Professor



ELECTRONICS AND COMMUNICATION ENGINEERING DEPARTMENT

THAPAR UNIVERSITY

(Established under the section 3 of UGC Act, 1956)

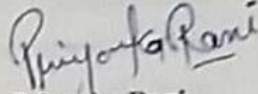
PATIALA-147004 (PUNJAB)

July, 2016

DECLARATION

I hereby declare that the work, which is being presented in the dissertation, entitled "**Comparative Performance Analysis of FWM effect in DWDM System**" is an authentic record of my own work carried out as requirement for the award of degree of Master of Engineering in Electronics and Communication Engineering submitted at Electronics and Communication Engineering department at Thapar University, Patiala under the guidance of **Dr. Hardeep Singh, (Assistant Professor)**, Electronics and Communication Engineering department and refers other research work which is duly listed in reference section. The matter presented in this dissertation has not been submitted in any other University/institute for award of degree.

Date: 13-07-2016


Priyanka Rani

Roll no. 801461020

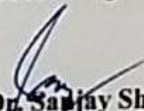
I certify that the above statement made by student is correct to the best of my knowledge and belief.

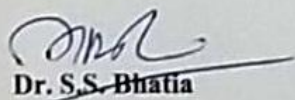
Date: 13.07.2016



Dr. Hardeep Singh
Assistant Professor, ECED

Countersigned by:


Dr. Sanjay Sharma
Professor and Head(ECED)
Thapar University, Patiala



Dr. S.S. Bhatia
Dean of Academic Affairs
Thapar University, Patiala

ACKNOWLEDGEMENT

First and foremost, I am beholden to the Almighty and I bow before him for his blessings and bestowing in me the grit and confidence to carry out this work.

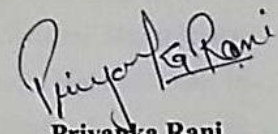
I would like to put on record my heartfelt and sincere gratitude to my research guide **Dr. Hardeep Singh**, Assistant Professor, Electronics and Communication Engineering Department, Thapar University, Patiala. I feel bound to be grateful to guiding soul for his valuable and constant support, advice, and encouragement.

I am also thankful to **Dr. Sanjay Sharma**, Professor and Head and **Dr. Amit Kumar Kholi**, PG Coordinator, Electronics and communication Engineering Department, for the motivation and inspiration that triggered me for this work.

I would like to thank entire faculty member, staff of Electronics and Communication Engineering Department, and then friends who devoted their valuable time and helped me in all possible ways towards successful completion of this work. I thank all those who have contributed directly or indirectly to this work.

Finally, I will remain obligated to and filled with appreciation towards my parents for their love, affection, sacrifices, perseverance, and prayers all through my life.

Date: 13-07-2016
Place: Patiala



Priyanka Rani
(801461020)

ABSTRACT

The non linear effects degrade the system performance. Non linearity effects arose as optical fiber data rates, transmission lengths, number of wavelengths and optical power levels increased, there study become important in DWDM system. The two types of nonlinearities occur in optical fiber are:-

- Stimulated scattering such as SRS and SBS
- Optical Kerr effect, due to changes in the refractive index of fiber with optical power

Depending upon the type of input sign Kerr-non-linearity represented in three different types of effects such as Self-Phase Modulation (SPM), Cross-Phase Modulation (CPM) and Four-Wave Mixing (FWM). At high power level, the inelastic scattering phenomenon can induce stimulated effects such as Stimulated-Raman Scattering (SRS) and Stimulated Brillion Scattering (SBS). Four-wave mixing (FWM) is one of the dominating degradation effects in wavelength-division-multiplexing (WDM) systems with dense channel spacing and low chromatic dispersion on the fiber. If in a WDM system the channels are equally spaced, the new waves generated by FWM will fall at channel frequencies and, thus, will give rise to crosstalk. Four-wave mixing (FWM) is a parametric process in which different frequencies interact and by frequency mixing generate new spectral components.

In this dissertation single and combined effect of input power, effective area, length of fiber and channel spacing are studied on FWM in Dense Wavelength Division Multiplexing (DWDM) optical communication system. The simulation is carried with eight channels in Optisystem software. Results show that increasing fiber length, effective area, channel spacing and decreasing input power reduces four wave mixing power to -70dbm. BER and Q factor are estimated using BER analyzer at the receiver side

CONTENTS

DECLARATION	ii
ACKNOWLEDGEMENT	iii
ABSTRACT	iv
CONTENTS	v
LIST OF ACRONYMS	vii
LIST OF FIGURES	viii
LIST OF TABLES	x
CHAPTER 1: INTRODUCTION.....	1-19
1.1 History of Optical Communication.....	1
1.2 General Overview of Fiber Optic Communication	2
1.3 Technology	3
1.3.1 Transmitter	3
1.3.2 Receiver	4
1.3.3 Drive Circuit.....	4
1.4 Types of Optical Fibers Used in Communication	4
1.5 Advantages of Optical Fiber	7
1.6 Splicing.....	8
1.7 Connection Losses in Optical Fiber	8
1.7.1 Intrinsic Loss.....	8
1.7.2 Extrinsic Loss.....	9
1.8 Multiplexing	10
1.8.1 Types of multiplexing techniques.....	10
1.9 Attenuation in Optical Fiber	12
1.10 Dispersion in Fiber	13
1.10.1 Types of dispersion.....	14
1.11 Compensation of Dispersion in Optical Transmission Line.....	15

1.12	Optical Amplifiers.....	16
1.12.1	Semiconductor optical amplifier.....	16
1.12.2	Erbium Doped Fiber Amplifier.....	17
1.13	Optisystem Software.....	18-19
CHAPTER 2: LITERATURE SURVEY.....		20-28
CHAPTER 3: NONLINEARITIES.....		29-39
3.1	Causes of Nonlinearities	29
3.2	Basics of Non Linearity	29
3.3	Types of Non-linearities	31
3.3.1	Self Phase Modulation.....	32
3.3.2	Cross Phase Modulation.....	34
3.3.3	Four Wave Mixing.....	35
3.3.4	Stimulated Raman scattering.....	37
3.3.5	Stimulated Brillouin scattering.....	38
CHAPTER 4: PROPOSED WORK.....		40-46
4.1	Introduction	40
4.2	Schematic Model.....	41
4.3	Simulation Set up.....	42
4.4	Methodology.....	43
4.5	Results and Discussion.....	46
CHAPTER 5: CONCLUDING AND FUTURE SCOPE.....		47
REFERENCES.....		48-51
LIST OF PUBLICATIONS.....		52

LIST OF ACRONYMS

WDM	Wavelength Division Multiplexing
TDM	Time Division Multiplexing
FDM	Frequency Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
CWDM	Coarse Wavelength Division Multiplexing
SPM	Self Phase Modulation
XPM	Cross Phase Modulation
FWM	Four Wave Mixing
SRS	Stimulated Raman Scattering
SBS	Stimulated Brillion Scattering
SOA	Semiconductor Optical Amplifier
EDFA	Erbium-Doped Fiber Amplifier
LED	Light Emitting Diode
LASER	Light Amplification by Stimulated Emission of Radiation

LIST OF FIGURES

- Figure 1.1:** Fiber optical communication
- Figure 1.2:** Single mode fiber
- Figure 1.3:** Multimode fiber
- Figure 1.4:** Single mode step index fiber
- Figure 1.5:** Multimode step index fiber
- Figure 1.6:** Graded index fiber
- Figure 1.7 :** Fusion splicing
- Figure 1.8:** Core diameter loss
- Figure 1.9 :** Numerical aperture loss
- Figure 1.10:** Lateral misalignment
- Figure 1.11:** Angular misalignment
- Figure 1.12:** TDM
- Figure 1.13:** WDM operating principle
- Figure 1.14:** Effect of dispersion
- Figure 1.15:** Graded index fiber
- Figure 1.16:** Semiconductor optical amplifier
- Figure 1.17:** Erbium doped fiber amplifier
- Figure 1.18:** Optisystem graphical editor
- Figure 3.1** f_1 and f_2 put inside the fiber
- Figure 3.2:** Generation of Side bands
- Figure 3.3:** Optical phase conjugation method

Figure 4.1: Schematic Model

Figure 4.2: Simulation set up

Figure 4.3: FWM Power against fiber length

Figure 4.4: FWM Power against input Power

Figure 4.5: FWM Power against effective Area

Figure 4.6: FWM against input Power for different length of fiber

Figure 4.7: FWM Power against input power for different Length of fibers with increased channel spacing

Figure 4.8: Comparison of Q factor and Fiber length for different channel spacing

Figure 4.9: Comparison of Q factor and input Power for different channel spacing

CHAPTER 1

INTRODUCTION

Fiber-optic communication is a method of sending information from one place to another by sending pulses of light through an optical fiber. Optics communication played important role in the advent of information age. The information carrying capacity of optical fiber is greater than its competitors: coaxial cable, microwave link and wires. The main benefits of fiber are:

- (a) High data carrying capacity
- (b) Low loss
- (c) Thousand of electrical links can be replaced by single high B.W fiber
- (d) No crosstalk

In long haul optical transmission, there is need for larger capacity. To increase data rate per channel and overall capacity, the number of channels per fiber are increased through wavelength division multiplexing or dense wavelength division multiplexing. Transmission impairments, which are not significant, add along the transmission link when amplifiers are used, so they cannot be ignored and put a new challenge to transmission design. Non linear effects are significantly more complex, they generate dispersion on each channel as well as cross talk between channels. Cross Phase Modulation (XPM), Four Wave Mixing (FWM), Self Phase Modulation (SPM) and Stimulated Raman Scattering (SRS) are examples of non-linear effects. FWM effect occurs when two or more wavelengths are launched in fiber, they generate a new wavelength which does not coincide with any of other wavelength

1.1 History of Optical Communication

Prior to the 19th century all communication systems were of very low data rate type and involved optical and sound signals such as horns and lamps. In eighteen century Greek used fire signal for announcement of certain events, call for help etc. During the second century optical signals were encoded using signaling lamps so that

any so that any message could be sent. Till the end of 18th century, there was no development in optical communication. The speed of communication link was limited due to atmospheric effects such as rain and fog made the transmission path unreliable. In 1835, Samuel F.B Morse invented the telegraph.

The first Commercial telegraph using wire cables was implemented in 1844 and further installation increased throughout the world.

The first telephone exchange was installed in 1878 at New Haven. In 1887, Heinrich Hertz discovered the long wavelength electromagnetic radiations. In 1895, Guglielmo Marconi discovered radio waves. Now the signals were transmitted over long distance using radio waves and microwaves. During the middle of twentieth century, it was realized that an increase of several orders of magnitude of bit rate distance product would be possible if optical waves were used as carrier.

1.2 General Overview of Fiber Optic Communication

The primary objective of optical fiber communication system is to transfer the signal information from source to destination. The basic components of the optical fiber communication system are shown in figure 1.1. Information source provides an electrical signal to a transmitter comprising an electrical stage.

Transmitter is used to convert an electrical signal into optical signal and send it into optical fiber. Optical source can be either semiconductor LASER or light emitting diode(LED). LED produce incoherent light with spectral width of 30-60nm, which is very useful for low frequency applications. LASER produces coherent light with spectral width < 5nm. For LASER there are drive circuit like bias control circuit, ECL and shunt drive circuit. For LED circuit like low impedance matching, coupled emitter switches are used. Receiver consists of an optical detector and provides demodulation of the optical carrier by driving electrical stage. Phototransistors, photoconductors and photodiodes are used for the detection of optical signal. Photodetector convert light into electricity using photoelectric effect. The two most common photo detectors are avalanche diode and p-i-n. Optical receiver should be bit rate data compression, sensitive of the signal and does not depend on bit pattern, holding time and particular range defined.

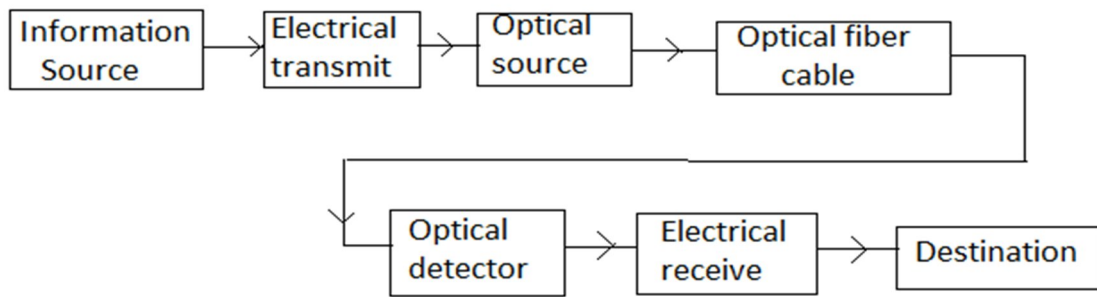


Figure 1.1: Fiber optical communication system

1.3 Technology

Today fiber optic communication include transmitter to convert an electrical signal into optical signal and send it to optical fiber, a cable consist of bundle of fiber, numbers of amplifiers to recover the signal at the receiver side and optical receiver.

1.3.1 Transmitter

Optical transmitter using semiconductor devices such as LED (light emitting diode) and LASER (light amplification by stimulated emission of radiations). Difference between LED and laser is

- a) LED produces incoherent light while laser produce coherent light. Coherence means constant phase difference.
- b) In LED, the principle of emission is spontaneous, but in laser principle is stimulated emission
- c) Light emitted from LED is incoherent with spectral width of 30-60 nm and it is useful for low frequency applications. Laser produces coherent light with spectral width of less than 5 nm.
- d) Output power is low in LED as compared to laser
- e) The speed of operation is slow in LED but speed of operation is fast in laser
- f) LED is easier to use because of low complexity. Laser is complex circuit because it needs thermal and optical stabilization circuits due to low amplification
- g) Life time of LED is large as compare to laser.

1.3.2 Receiver

It includes photodetectors, voltage amplifier, a decision circuit that gives the exact information signal that is transmitted at transmitter side. Photodetector is function of photo diode that convert light into electricity. Optical to electrical conversion produce a digital signal in electrical domain, in electrical domain the signal is attenuated and distorted when passing through the channel. Such clock recovery from data is performed by PLL applied before the data is passing through the channel. The two most common photodetectors are p-i-n and avalanche diode. Optical receivers do detection in two ways direct detection and coherent detection. Pn diode and p-i-n photo diode use direct detection. Coherent detection based receiver use monochromatic laser as local oscillator. It is difficult to maintain phase information required for coherent detection since Semiconductor laser has non-zero line width, the transmitted signal consist of a number of frequencies with varying phases and amplitude. The effect is that the phase of transmitted signal experiences significant fluctuations around the desired phase. These phase fluctuations make it difficult to recover the original phase information from the transmitted signal thus limiting the performance of coherent detection system

1.3.3 Drive Circuit

It is used to switch the current varied in the range of 10 to 1000 mA. For LED there are drive circuits like common emitter, low impedance matching, coupled emitter switched, trans conductance drive circuit. For LASER shunt drive circuit, bias control circuit, ECL compatible drive circuit.

1.4 Types of Optical Fibers Used in Communication

Single mode fibers: The fiber which allows the propagation of only one is called single mode or monomode fiber. The propagation of single mode is shown in figure 1.2. The number of modes travelling through the fiber is generally depends upon V number. For single mode fiber V number is 2.405. In single mode fiber, launching of light and its fabrication is very difficult so the fiber is very expensive.

But the transmission loss and degradation of the signal is very small. So the single mode fibers are very useful in long distance communication.

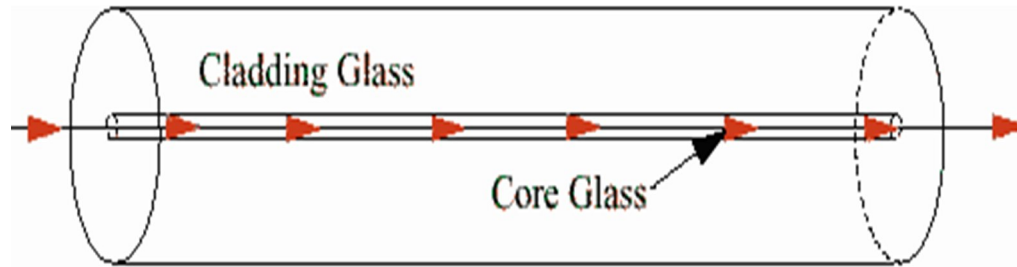


Figure 1.2: Single mode fiber

Multimode fibers: The fiber which allows the propagation of more than one mode is called multimode fiber. In multimode fiber, the light travel down a much larger path, allowing the light to go down several modes/ paths. A large core diameter and high frequency are required for the propagation of a number of modes. The number of modes is given approximately by:

$$M = \frac{\pi d^2 \Delta n^2}{4\lambda^2}$$

The refractive index difference and diameter of the core are larger in multimode fiber than in single mode fiber. Fabrication of the fiber and launching of light into the fiber is easy than single mode fiber. These fibers are used in local area networks.

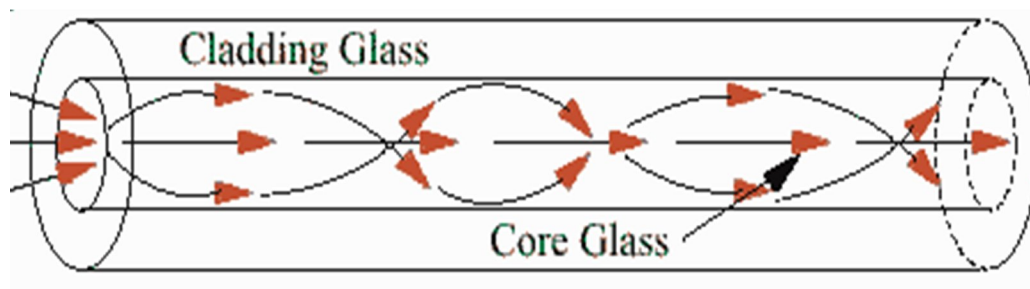


Figure 1.3: Multimode fiber

Based on the refractive index profile we have two types of fibers:

- (a) Step index fiber
- (b) Graded index fiber

Step index fiber: In the optical fiber, when the refractive index of core is constant throughout and goes a step change at the core cladding interface is known as step index fiber. As shown in figure 1.4, there are two types of step index fiber. Figure 1.4 shows a single mode step index fiber which allows the propagation of only one transverse electromagnetic mode. The core diameter of single mode fiber is 2-10 μm . Due to one mode propagation, it has low intermodal dispersion. Figure 1.5 shows a multimode step index fiber with a core diameter of 50-100 μm . It allows the propagation of many modes within the fiber. Dispersion may occur in multimode fiber due to different group velocities of the propagation modes.

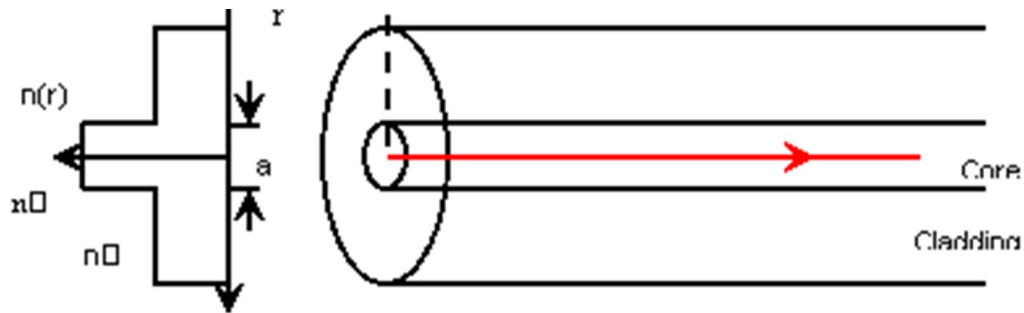


Figure 1.4: Single mode step index fiber

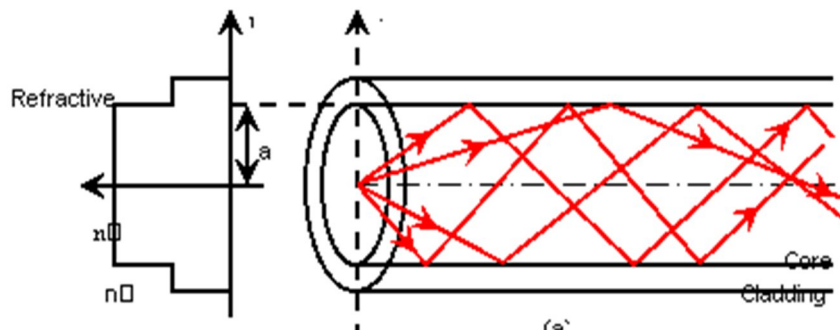


Figure 1.5: Multimode step index fiber

Graded index fiber: In the optical fiber, when the refractive index of core is made to change in the parabolic manner is called graded index as shown in figure 1.6. Graded index fiber reduces the critical angle to minimum for total internal reflection. It also helps to reduce the intermodal dispersion. The maximum value of refractive index is at the centre of the core. The multimode graded index fibers exhibit less intermodal dispersion than multimode step index fibers due to their refractive index profile.

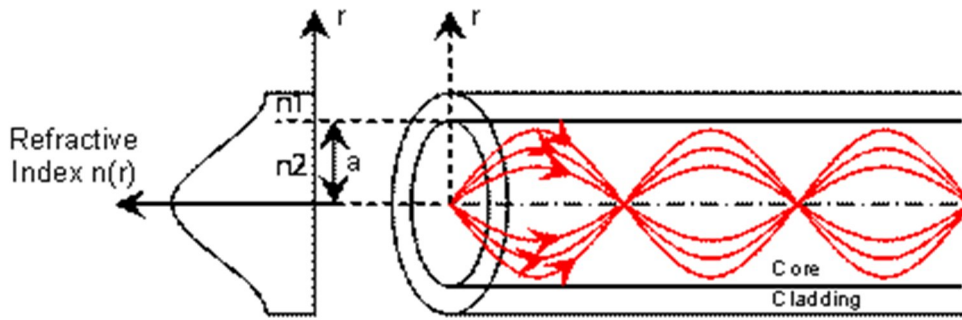


Figure 1.6: Graded index fiber

1.5 Advantages of Optical Fiber

- **High bandwidth:** It carry high speed signal over a long distance without using repeater. The information carrying capacity increases with frequency i.e. few MHz/Km , fiber cable has bandwidth of 400 MHz/Km
- **High carrying capacity:** optical fibers are thinner than copper wires, so more fibers can be bundled into a cable. It allows more channels to come through the cable into cable TV box
- **Less signal degradation:** The loss of signal in optical fiber is less than in copper wire. Light signals from one fiber do not interfere with other fibers in the same cable.
- **Data security:** For carrying the data, fiber is most safe medium. If the cable is tapped, is very easy to check, because the cable leaks light, causing the entire system to fail.
- **Eliminating spark hazard:** some electrical transmission create small spark, these spark no longer danger but bad in oil refinery or chemical plant. This small spark can create big explosion. The fiber is a dielectric, so it does not present spark hazard.
- **Ease of installation:** fiber cable is easy to install since they have small size, light

weight, flexibility and small radii. By increasing capacity of transmitting, more signal of fiber cable make fiber thicker and more rigid.

1.6 Splicing

Splicing is permanent connection of two pieces of an optical fiber. Splicing is of two types, mid spam and pigtail. Connecting the two cables in between is called mid spam. Pigtail consist of fiber that has a factory installed connector at one end with other end free for splicing

- **Fusion Splicing:** it is the process of fusing or welding two fibers together by an electric arc. A machine is used to precisely align the two fiber ends, then fiber ends are welded together using heat/ electric arc. This produces a continuous connection and very low loss. Fusion splicing is mostly used method because it has low cost and provide strongest joint between two fibers.
- **Mechanical Splicing:** this method is generally used for quick repair. Two pieces of stripped cleaved and cleaned fibers are inserted into a splicing device with their ends directive toward each other

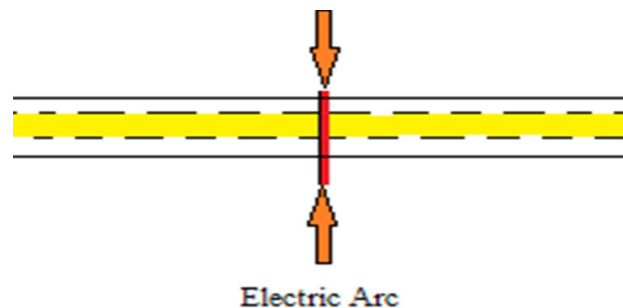


Figure 1.7: Fusion splicing

1.7 Connection Losses in Optical Fiber:

1.7.1 Intrinsic Loss: for any type of splicing like mid spam or pigtail, connection losses are introduced if all light is not transferred to other fiber. Basic reason for this misalignment/ mismatch between two fibers is

(a) Core diameter mismatch: as shown in fig 1.8, core diameter mismatch occurs when the core diameter of the receiving fiber is less than the core diameter of transmitting fiber. Then core diameter loss is calculate as given below. Where a_1 is the radius of transmitting fiber and a_2 is the radius of receiving fiber

$$\text{Core diameter Loss} = 20 \log \left[\frac{a_1^2}{a_2^2} \right]$$



Figure 1.8: Core diameter loss

(a) Numerical aperture mismatch: numerical aperture loss occurs when the numerical aperture of receiving (NA_2) fiber is less than the numerical aperture of transmitting fiber (NA_1). Numerical aperture loss can be calculated mathematically as.

$$\text{Numerical aperture Loss} = 20 \log \left[\frac{NA_1^2}{NA_2^2} \right]$$

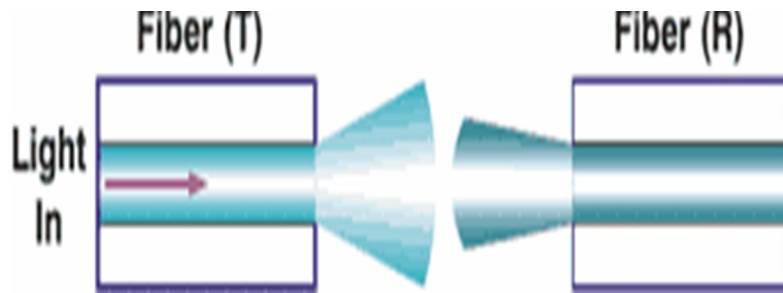


Figure 1.9: Numerical aperture loss

1.7.2 Extrinsic Loss: the losses which occur due to misalignment are called extrinsic losses. Lateral misalignment and angular misalignment are types of extrinsic losses.

- (a) Lateral Misalignment: a connector should align the fibers on their centre axis, but when one fiber's axis doesn't coincide with other fiber axis then lateral misalignment occurs as shown in figure 1.10.

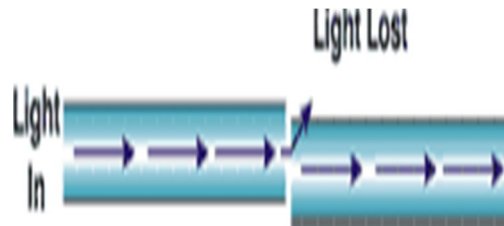


Figure 1.10: Lateral misalignment

- (b) Angular Misalignment: the ends of fibers should be perpendicular to the fiber axes and to each other. Failure to be perpendicular is called angular misalignment as shown in figure 1.11.

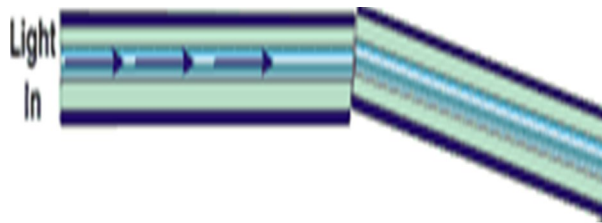


Figure 1.11: Angular misalignment

1.8 Multiplexing

To combine multiple signals into a single line of transmission is called multiplexing. The device that combines multiple signals into one line is called multiplexer. The combined signals are separated by the help of de-multiplexer, at the receiver side.

1.8.1 Types of multiplexing techniques:

- (a) TDM (time division multiplexing)
- (b) WDM (wavelength division multiplexing)
- (c) FDM (frequency division multiplexing)

TDM: in this technique different cables share same channel on the basis of time. If one cable is assigned a specific time slot during the transmission of a signal then no other cable is allowed to send data during this time slot. So in TDM multiple signals are transmitted, but each one is sent in parts, as shown in figure 1.12. Therefore it is less efficient technique.

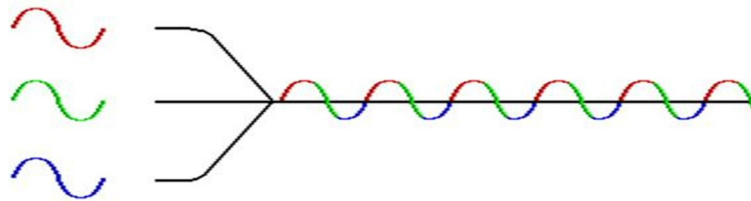


Figure 1.12: TDM

WDM: on the basis of wavelength, different cables use the same fiber. WDM is designed to use the high bandwidth capacity of optic fiber cable. Each WDM fiber has certain bandwidth-the range of frequencies it can carry. WDM operate in multimode fiber with core diameter of 50 μm and in single mode fiber with core diameter of 9 μm . in WDM every user can transmit information at the highest rate possible all the time. WDM does not change the transfer rates in proportion to the number of users on the line. Another large benefit to WDM is that it increases the amount of information that can be transferred without significant loss of signal integrity. The conceptual view of WDM is shown in figure 1.13

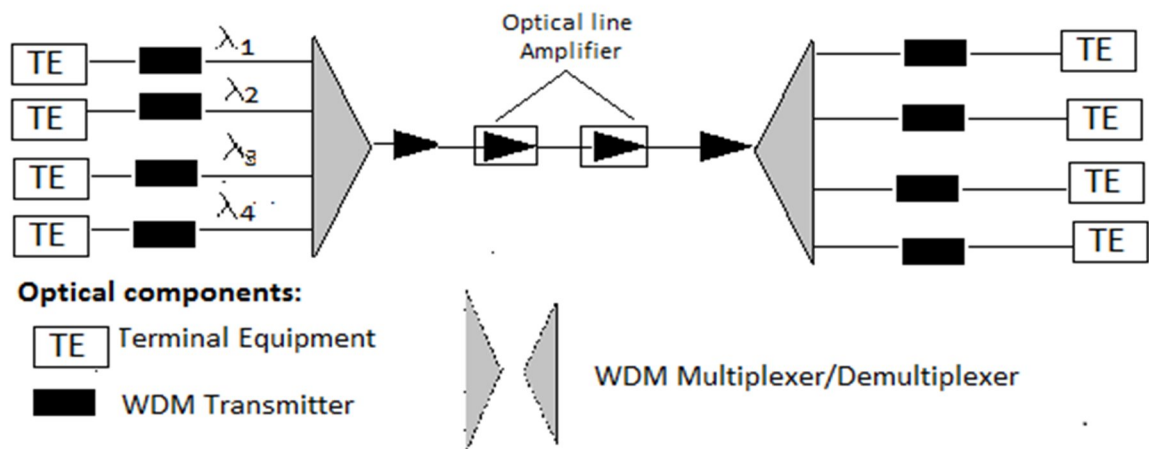


Figure: 1.13 WDM operating principle

WDM divided into different types:

- CWDM (coarse wavelength division multiplexing)
- DWDM (dense wavelength division multiplexing)

1) CWDM

CWDM is used to increase the bandwidth of optical fiber by multiplexing several wavelengths onto it. CWDM uses up to 18 wavelengths. Typically, only the upper 8 of the 16 wavelengths are used. To use the desired wavelengths, CWDM initially filter the light. Secondly, multiplex/ demultiplex wavelengths which are used on a single fiber link. The 1550 band and 1310 band are divided into smaller bands, each only 20 nm wide in CWDM space. The wide channel spacing of CWDM, compared to DWDM allows for the use of cheaper CWDM network components.

2) DWDM

DWDM is used to increase the bandwidth of optical fiber by multiplexing several wavelengths onto it. DWDM uses up to 18 wavelengths. WDM, CWDM and DWDM are based on the same concept of multiple wavelengths on single fiber but different in number of wavelengths and spacing. For 40 channels, DWDM uses channel spacing of 100GHz, for 80 channels 50 GHz. EDFA provides amplification in c-band. Raman provides amplification in L-band. In CWDM no amplification occurs.

c) FDM: in FDM, several signals are combined for transmission on a single channel. Each signal is assigned a different frequency. To prevent interference, the channels are separated by guard bands, which is unused portion of the spectrum. It is used in radio, TV broadcast and mobiles etc. Service provider sends multiple signals simultaneously to all subscribers without any interference and at the receiver end subscriber must tune to the accurate frequency to access channel.

1.9 Attenuation in Optical Fiber

Attenuation in optical fiber means reduction of signal power as signal propagates over some distance. Minimum power required to detect the signal is called receiver sensitivity.

Fiber with low attenuation reaches to the receiver with more power than a fiber with higher attenuation. Let $P(0)$ is the optical power at transmitter and $P(L)$ be power of optical pulse at distance L km from the transmitter and A is attenuation constant of fiber measured in dB/Km.

$$P(L) = 10^{-\frac{AL}{10}} P(0) \quad 1.1$$

From equation 1.1, link length L_{\max} can be calculated. The power of the optical pulse at the transmitter $P(L)$ must be greater than receiver sensitivity(P_r)

$$L_{\max} = \frac{10}{A} \log_{10} \frac{P(0)}{P_r} \quad 1.2$$

Therefore maximum distance between amplifiers (or between the transmitter and receiver) depends more heavily on attenuation constant A than the power launched in fiber.

1.10 Dispersion in Fiber

Dispersion of transmitted optical signal causes distortion for both digital and analog transmission along optical fiber. Dispersion within fiber causes broadening of transmitted pulses as they travel along the fiber. As a result each pulse broadens and overlap with its neighboring eventually becomes indistinguishable at the receiver output. This effect is known as ISI (intersymbol interference). This pulse broadening or spreading reduces the information capacity and bandwidth. When the pulse spreads, it spreads enough to interfere with neighboring pulse as shown in figure 1.14, which leads to intersymbol interference. For no longer overlapping of light pulses on an optical fiber length the bit rate should be $B_T \leq \frac{1}{2T}$

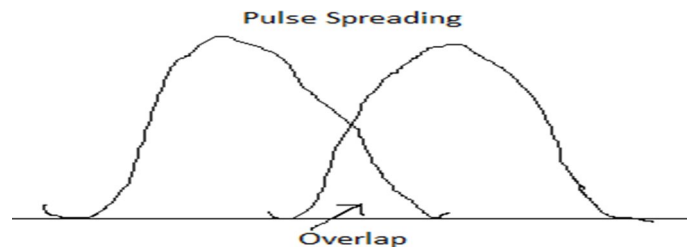


Figure 1.14: Effect of dispersion

1.10.1 Types of dispersion

(1) Intermodal dispersion

(2) Intra-modal dispersion

1) Intermodal dispersion: it occurs in multimode fiber. In multimode fiber, modes travel at different velocity due to different angle of incidence at core-cladding boundary. So different rays of light reach at other end of fiber at different times, resulting in a broadening of pulse. The effect of intermodal dispersion can be reduced by following ways:

- Using small core diameter
- Using single mode fiber
- Using graded index fiber, in which the region between the core and cladding of the fiber consists of gradual changes in the refractive index of fiber as shown in figure 1.15

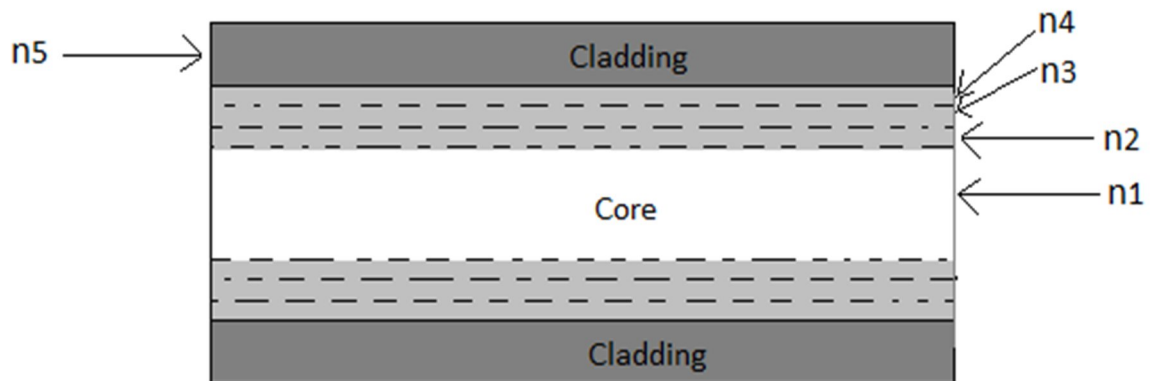


Figure 1.15: Graded index fiber

2) Intra-modal dispersion: it is caused due to the fact that different wavelengths travel at different speed within same mode along the fiber. Optical source emit a band of frequencies, then there may be propagation delay between the different spectral components of transmitted signals. This causes the broadening of each transmitted mode and hence intermodal dispersion occurs. Intermodal dispersion is result of three dispersions:

- (a) Material dispersion
- (b) Waveguide dispersion
- (c) Polarisation mode dispersion

(a) Material dispersion: material dispersion occurs because spreading of pulse is dependent on wavelength's interaction with the refractive index of the core. Different wavelengths travel at different speed in material. Source spectral width is function of material dispersion. The range of wavelengths that can propagate in fiber is called spectral width. When phase velocity of plane wave traveling in dielectric medium varies nonlinearly with wavelength then material is said to exhibit material dispersion and when second differential of refractive index with respect to wavelength is non-zero.

(b) Waveguide dispersion: it is caused because of propagation of different wavelengths that depend on waveguide characteristics such as refractive index, shape of core and cladding. It occurs in single mode fiber because optical energy travels through the core and cladding with different indices. Multimode waveguide dispersion is small as compared to material dispersion. Waveguide dispersion is usually neglected in multimode fiber.

(c) Polarisation mode dispersion: single mode fiber supports two perpendicular polarizations of transmitted signal. If fiber is free from all stresses and perfectly round then both polarization mode will travel at exactly same speed resulting in zero dispersion while practical fibers are not perfectly round so perpendicular polarization travel at different speed and reach at the end of fiber at different time. PMD occurs when there is difference in refractive index along x axis and y axis. The difference is called Bire fringes $B = \eta_x - \eta_y$.

1.11 Compensation of Dispersion in Optical Transmission Lines

- (1) Dispersion compensating fiber (DCF)
- (2) Dispersion compensating grating (DCG)

(1) Dispersion compensating fiber: the main problem of DCF is high attenuation.

18-20 Km of DCF is required to compensate 120 Km. It results in 0.8-0.1 dB/Km attenuation. So to reduce attenuation interim fiber is used. Hence there should be ideal placement of dispersion compensating fiber in single mode fiber. All the effects in dispersion compensation technique are wavelength dependent. Therefore DCF should be designed for dispersion not only single wavelength but over entire band.

(2) Dispersion compensating grating: grating is a periodic structure i.e. there is a periodic change in value of refractive index of core. At every change of refractive index, a small segment of light is reflected at every segment. All these reflected segments of light are combined into one reflected beam provided Bragg condition is maximum.

$$2 \eta_{\text{eff}} \Lambda = \lambda_B$$

λ_B =Bragg wavelength, η_{eff} = effective refractive index, Λ =grating period

1.12 Optical Amplifiers

Optical amplifier is a device that amplifies an optical signal, without the need to convert it into electrical signal. It is used in long distance communication. Optical amplifiers are used for enhancing the signal strength before demultiplexing or after multiplexing, but both introduce loss in the system. In single mode fiber, the effects of fiber dispersion are small but main limitation is fiber attenuation. Therefore complete regeneration of signal is not required, simple amplification of optical signal is sufficient. Thus in line amplifier is used to compensate transmission loss. Pre amplifier is used before the optical receiver. A weak optical signal is amplified by pre amplifier before photo detection so that S/N ratio degradation caused by thermal noise in the receiver is suppressed. Power or boost amplifier application include placing the device immediately after an optical transmitter to enhance the transmitted power.

1.12.1 Semiconductor optical amplifier

Semiconductor optical amplifier use the semiconductor medium to provide the gain medium. SOA is small in size and electrically pumped. These don't require feedback mechanism. They can work in 1300-1500 with lower attenuation window. Semiconductor

optical amplifiers are of two types: Fabry perot amplifier and travelling wave amplifiers. In FPA, two cleaved faces of semiconductor act as partially reflecting end mirrors that forms a fabry perot cavity. the natural reflectivity is 32%, signal gets amplified as it reflects back and forth between the mirrors until it is emitted a higher intensity. Structure of traveling wave amplifier is same as that of FPA except that end faces are anti reflection coated at an angle so that internal reflection don't take place. Thus the input light is amplified only once during a single pass through traveling wave amplifier.

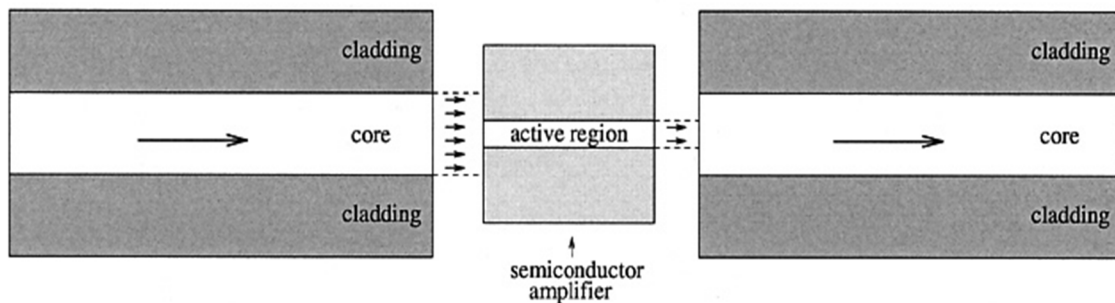


Figure 1.16: Semiconductor optical amplifier

It has reflectivity 0.01%. TWA is widely used than FPA because they have large optical bandwidth and high saturation power. Semiconductor optical amplifier are used in switches, filters and modulators. These can be integrated along with other semiconductor and photonic devices into one chip called OEIC (Opto electronic integrated circuit).

1.12.2 Erbium Doped Fiber Amplifier

Erbium doped fiber amplifier use a doper fiber as gain medium to amplify the signal. A piece of fiber working as an active medium is heavily doped with ions of erbium. Both the optical information and pumping beam are coupled in WDM coupler. These two beams travel along the doped section of fiber where the information signal is amplified by pumping signal and losses its power. It means pumping light gives its power to information signal and dies. Amplification in EDFA occurs through stimulated emission mechanism. Energy from the pumping signal excites erbium ions at the upper energy band. The information signal stimulate transition of excite ions at the upper energy band. These transitions result in radiation of photons with same energy i.e same wavelength as

input signal. Therefore EDFA has wide gain wavelength. If the pump light is usually injected from the same direction as the signal flows this is known as co-directional pumping and if pump light is injected in opposite direction to the signal flow that is known as counter directional pumping. This provides higher output power but produce great noise. Pumping at 980 nm is preferred since it produces low noise than 1480 nm. To equalize the gain of erbium doped fiber amplifier notch filter is used.

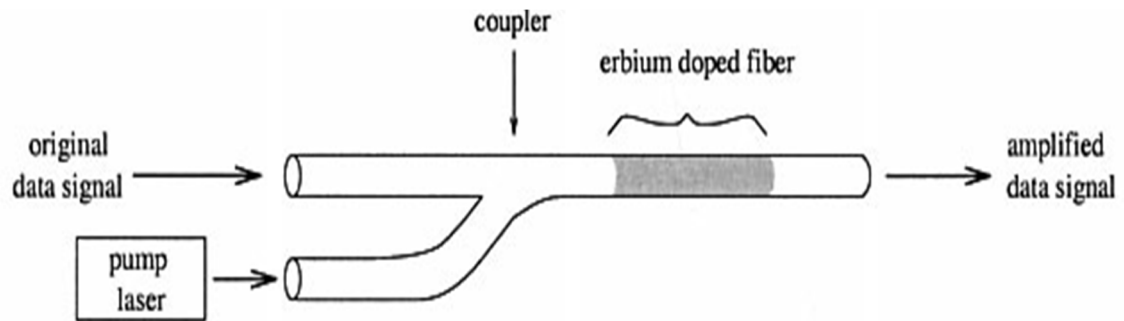


Figure 1.17: Erbium doped fiber amplifier

1.13 Optisystem Software

Optisystem software is an innovative optical communication system simulation package that designs, tests, and optimizes virtually any type of optical link in the physical layer of a broad spectrum of optical networks, from analog video broadcasting systems to intercontinental backbones (Optisystem reference guide 2002). Optisystem is a standalone product that does not rely on other simulation frameworks. It is physical layer simulator based on the realistic modeling of fiber-optic communication systems. It possesses a powerful new simulation environment and a truly hierarchical definition of components and systems. Its capabilities can be extended easily with the addition of user components, and can be seamlessly interfaced to a wide range of tools. The extensive library of active and passive components includes realistic, wavelength dependent parameters. Parameter sweeps allow the user to investigate the effect of particular device specifications on system performance. Optisystem calculates the signals using the appropriate algorithms related to the required simulation by determining the order of execution of component modules according to the selected data flow model. The main data flow model that addresses the simulation of the

transmission layer is the Component Iteration Data Flow (CIDF). The CIDF domain uses run-time scheduling, supporting conditions, data-dependent iteration and true recursion. In order to predict the system performance, Optisystem software calculates parameters such as BER and Q-Factor using numerical analysis or semi-analytical techniques for systems limited by intersymbol and noise

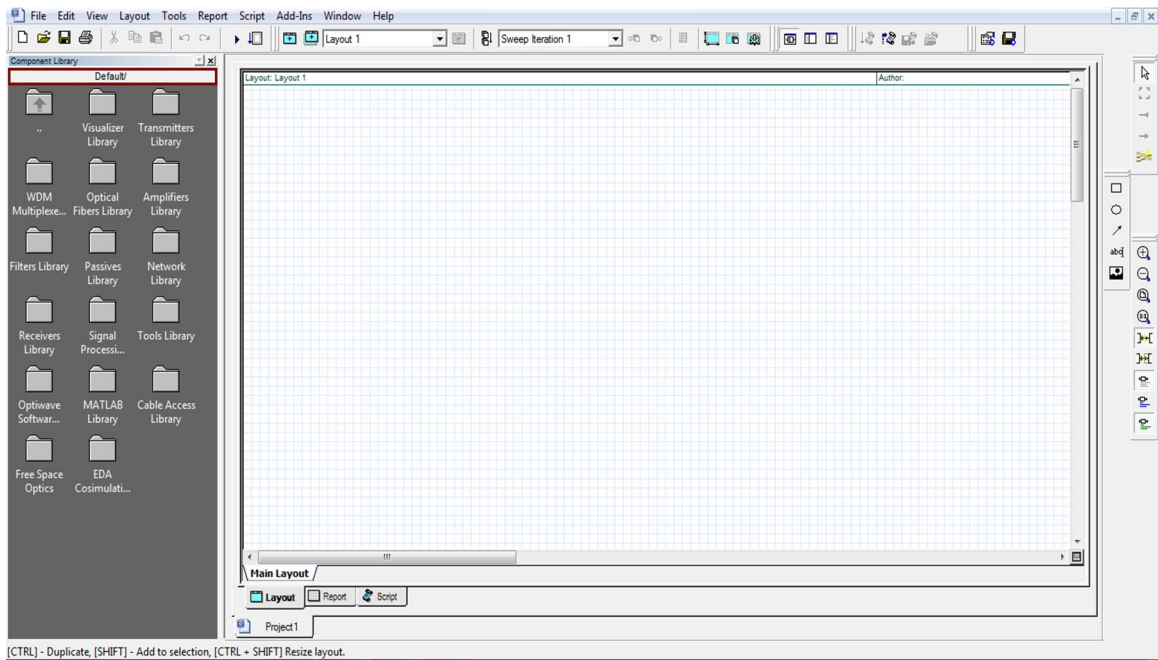


Figure 1.18: Optisystem graphical editor

CHAPTER 2

LITERATURE SURVEY

The book “Non linear fiber optics” by G.P Aggarwal provided the mathematical model of non linear effects. Types of non-linear effects such as XPM, SPM, and FWM are discussed in brief. Aggarwal discussed the case of equal bit rates and equal received power in all channels and observed that the crosstalk from each channel should be below -12 dB. Further he proposed that the minimum channel spacing of about 4 or 5 times the bit rate is dependent upon the filter bandwidth whether it is 2 or 3 times respectively. To reduce the power penalty below 0.1 dB, crosstalk should be less than -18 dB and should have a minimum channel spacing of about 10 times the bit rate.

M Arumugam [2] gives the overview of fiber optic communication system. In this paper the history of optical communication has been discussed. The different types of fibers such as step index fiber, graded index fiber, single mode fiber and multimode fiber are discussed. The soliton pulses are highlighted in optical communication. This paper discusses how optical pulses are useful for high quality telecommunication at a lower cost.

Monika et al. [3] in this paper, the authors presented the design, implementation and performance analysis of FWM in optical communication system. The system has been designed for different number of input channels like 2,4,6,8,12 input channels and for various values of channel spacing i.e., 6.25GHz, 12.3GHz, 25GHz, 40GHz, 50GHz. The results show that as the number of users/channels is increased, the interference also increases and thus, the four wave mixing effect also increases. The eye diagram becomes less clear with the increase in number of input channels. Also, it increases the BER and decreases the Q-factor. The authors thus concluded that the effect of FWM is minimum when there is least number of users.

S.P. Singh et. al. [4] described the basics of non-linear effects, types of non linear effects which degrade the system performance and comparison between different non

linear effects such as self phase modulation, cross phase modulation and four wave mixing. In FWM dispersion shifted fiber is applied because if dispersion is present then four wave mixing effect can be reduced. If power is below 19.6mw SPM effect is negligible.

Surinder Singh et. al. [5] described the four wave mixing (FWM) effect in different spectral efficient orthogonal modulation formats at equal channel spacing of 100 GHz and 50 GHz to design long haul wavelength division multiplexing (WDM) optical system. Further, the comparison of reduction of FWM for existing and proposed modulation format have been analyzed by varying the laser input power from -10 dBm to 10 dBm. It is observed that FWM effect more on three-dimensional orthogonal modulation format; it is difficult to design practical long haul WDM communication system as compared to other modulation formats.

Gurpreet Kaur et. al. [6] described effect of FWM (four wave mixing) in WDM systems. There are a number of optical nonlinear effects in optical fibers, such as stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), carrier-induced phase modulation and four-wave mixing (FWM). Out of these SRS and FWM are the dominant effects. In this paper, an algorithm has been suggested to study the effect of FWM in the total system noise considering the combined effect of SRS and FWM in the presence of amplified spontaneous noise (ASE). It has been found from the study that to maximize the signal-to-noise ratio of the transmitted signal in a WDM system, FWM noise needs to be reduced as this is the dominant noise factor.

David F.Geraghty et. al. [7] discussed that four wave mixing (FWM) in semiconductor optical amplifiers is an attractive mechanism for wavelength conversion in wavelength division multiplexed (WDM) systems since it provides modulation format and bit rate transparency over wide tuning ranges. They presented a series of experiments evaluating several aspects of the performance of these devices at bit rates of 2.5 and 10 Gbps. They also presented time resolved spectral analysis of wavelength conversion

Yasin M. Karfaa et. al. [8] presented a comprehensive theoretical study of four wave mixing in optical fiber with exploring four fiber types. They integrated corresponding system of equations numerically and described the channels interaction phenomena such as four wave mixing. They evaluated the system performance through determining the average bit error rate relation with both of the frequency and wavelength of transmitted optical channels in the presence of four-wave mixing crosstalk noise

S Sugumaran, Manu Aggarwal, P Arulmozhivarman et. al. [9] discusses the Four Wave Mixing efficiency (FWM) in DWDM systems based on Channel Spacing and Dispersion Coefficient for different fiber lengths. The design of the FWM was simulated with the OPTISYSTEM 7.0 tool and analyzed using the eye pattern method with respect to BER. This paper also shows the effect of chromatic dispersion on FWM in terms of input/output spectrums and eye diagrams. Results of the simulation show that FWM effect can be reduced by using unequal channel spacing and it is reduced more when the dispersion coefficient is increased

John M. Senior, [10] provides the background material and the mathematical tools needed for understanding the various nonlinear effects. Starting from the Maxwell's equation, the wave equation in a nonlinear dispersive medium is used to discuss the fiber modes and to obtain the basic propagation equation

S.P. Singh, et. al [11] describe about four wave mixing i.e. using dispersion shifted fiber. By using dispersion shifted fiber effect of four wave mixing is reduced. FWM effect is reduced by placing unequally spaced frequencies, it leads to increase the bandwidth. With lesser number of four wave mixing components, better bandwidth is obtained.

Gurmeet Kaur [12] presented a work about combination of SRS and FWM in amplifier spontaneous noise that produce optimized inter channel separation. In the presence of ASE minimum noise is achieved. Enhanced capacity and flexible optical networks are advantages of WDM system. For long distance transmission erbium

doped fiber amplifier is used, without the use of regenerative repeater. In this paper an algorithm for optimization of inter-channel separation has been discussed. Transmission distance depends on different parameters such as number of channels, fiber length, channel spacing and amplifier spacing. By varying these parameters maximum transmission distance is achieved.

V. Sharma et. al. [13] Implemented the 80 Gbps DWDM systems over the distance of 100km in the presence of FWM under the impact of equal and unequal channel spacing. It was observed that the reduction in channel spacing to accommodate optical channel in the presence of FWM, results in degradation of the performance. The proposed schemes were compared to each other and further observed the improvement in received power with unequal channel spacing as compare to equal channel spacing.

R. S. Kaler et al [14] presented At 10 Gbps, RZ-DPSK gives the least value of figure of merit, Pmax whereas at 40 Gbps, it gives the highest value of Pmax. At 10 Gb/s SPM induced limitation is relatively insensitive to the signal modulation formats. At 40 Gb/s the system tolerance to SPM induced non-linear distortion is strongly affected by signal modulation formats.

B. Yao et. al. [15] discussed the transmission characteristics in a WDM system using a wideband OPC. It was reported that, when the dispersion slope of the dispersion flattened fiber is 0.001ps/km/nm^2 the pulse shapes are distorted considerably by FWM, while pulse shapes are kept good in the case of 0.02ps/km/nm^2

Chiang et al. [16] reported that the phase modulation induced by cross phase modulation is Inversely proportional to the signal base band modulation frequency

P.L.Li et. al. [17] presented a comprehensive broad-band model of tunable wavelength converter based on four-wave mixing (FWM) in semiconductor fiber ring laser. They considered the critical factors like the material gain profile, the longitudinal variation of the optical field, the Carrier density and the broad-band spontaneous noise emission in

the model. They investigated the effects of the input signal power injection current, the coupling of the output coupler and the lasing wavelength on the performance of the wavelength converter, such as the conversion efficiency.

Iftikhar Rasheed et. al. [18] presents the Non-linear Effects at various Power Levels and Channel Counts on the Performance of DWDM based Optical Fiber Communication System. The analysis of XPM, FWM and SRS effect in DWDM fiber optics communication system is done. The analysis is done on the basis of result obtained from simulation in Optisystem. This paper shows how the non linearity's i.e. XPM, FWM and SRS increase in optical fiber communication system by increasing the input power and number of input channels. Further, some effective techniques for compensating the XPM & FWM effects are discussed briefly in this paper.

Borja Vidal, Member, IEEE, Alexander Bockelt et. al. [19] described the Enhanced multiple four-wave mixing (FWM) processes in nonlinear fiber by phase modulation of the pump carrier, for harmonic mixing multiplication of microwave signals. The enhancement of cascaded FWM by phase modulation in the case of small spacing between pump carriers (10 GHz) is studied. Experimental results show that microwave signals in the V-band can be generated from a tone in the C-band through external amplitude modulation and optical nonlinear harmonic multiplication. A harmonic multiplication factor of 13 has been demonstrated using the proposed technique. The unconverted microwave signals show no additional degradation in phase noise due to the photonic nonlinear processes besides the inherent phase noise increment due to the multiplication process.

Qiang Hao and Heping Zeng et. al. [20] demonstrated high-power yellow and near infrared laser emissions by cascaded FWM in a nonlinear Yb-doped fiber amplifier, generating average power of 2.0 W at 830 nm and 0.35 W at 594 nm. Moreover, multiple cascaded four-wave mixing processes which generated SC covering more than four octaves from 398 to 1700 nm was also investigated by seeding the Yb-doped fiber amplifier with Q-switched mode locked laser pulses. The group-velocity matching for

pump and parametric waves was fulfilled by compensating for the material dispersion with multimode dispersion in the nonlinear fiber amplifier. The proposed configuration is anticipated to stimulate multiple applications for SC-based microscopy and spectroscopy.

Amarpal Singh, Ajay K. Sharma et. al.[21] investigate the methods for Four Wave Mixing (FWM) suppression. Modified techniques equal and unequal-channel spacing with polarization, equal channel spacing with alternate channel delay, optical coupling and varied laser power have been proposed to reduce the impact of FWM on Dense Wave Length Division Multiplexing (DWDM) optical communication system. Further the comparison of reduction of FWM for existing and proposed techniques has been discussed by varying the dispersion of fiber. It has been observed that the suggested techniques are simpler to design optical communication system and superior to the existing methods.

H.J. Abed, N.M. Din, M.H. Al-Mansoori et. al. [23] described the various suppression techniques to suppress the four wave mixing and to improve the system performance. These techniques are individual and combined effects of high dispersion on FWM, using hybrid WDM and time division multiplexing, optical code division multiple access, optical amplifiers etc. The reduction techniques of FWM effect were compared according to the benefits and weaknesses of each technique in the application of WDM communication systems.

M. Noshad, A. Rostami et. al. [24] described the four wave mixing minimization in wavelength division multiplexing systems using the asymmetrical dispersion management fibers. A theoretical expression for FWM induced power penalty in asymmetrical dispersion-managed fibers has been derived. The power penalty in these fibers is analyzed for various values of channel spacing, maximum dispersion and number of sections in different channels. Using numerical simulations, it is illustrated that the FWM induced power penalty is minimized for the case of two fiber sections with unequally special lengths and symmetrical dispersion values.

Rajneesh kaler et. al. [25] compared the four wave mixing effect for different values of ultra low channel spacing and the performance has been evaluated in terms of output spectrums, eye diagrams, BER, eye opening and Q-factor. The simulation results reveal that four wave mixing is minimum at high wavelength spacing. Further, it has been observed that on increasing the spacing between input channels, their interference with each other decreases and thus, the four wave mixing effect also decreases. At ultra low channel spacing of 6.25 GHz, the four wave mixing effects are maximum.

Gurpreet Kaur et. al. [26] described the Suppression of four wave mixing in wavelength division multiplexed system with hybrid modules. Two different configurations of optical phase conjugator, dispersion compensating fiber and fiber Bragg grating have been investigated. These configurations are further compared with the conventional schemes. Several link configurations have been compared and investigated the potential for inter-subcarrier four wave mixing suppression by means of midway fibers plus hybrid modules.

T. Sabapathi et. al. [27] described the compensation of fiber non-linear effects by maximum likelihood sequence detector. It is shown that a low complexity maximum likelihood sequence detector with proper metrics can achieve better results. Computational complexity grows exponentially with the length of the channel impulse response and makes it unsuitable for high data rates. To practically enable uncompensated long haul with MLSD, complexity must be minimized. While in the linear regime such a model is available and linear impairments such as chromatic dispersion and polarization-mode dispersion can be almost fully compensated.

C. T. Politi et. al. [28] investigated the wavelength dependent behavior of a wavelength converter and the requirement for a widely tunable converter. They also studied a configuration for extinction ratio improvement.

Ivan B. Djordjevic [29] described simple expression of transmission limitation of wavelength division multiplexing. In line optical amplifier is also applied. In the presence of ASE noise two non-linearity's FWM and SRS are considered. Different parameters are applied which are number of channels, spacing and bandwidth and find one that increases the transmission distance. In these non linearity's optimum spacing maximize the transmission distance. Different configurations of dispersion compensating fiber are also discussed.

A. Nandhini and K. Gokulakrishnan [30] discussed various combinations of optical amplifiers for a dense wavelength division multiplexed system with different modulation formats. MDRZ modulation format shows maximum Q factor, comparing to CSRZ and DRZ modulation format, and so it is said to be an optimized modulation format. EDFA-RAMAN, SMF+EDFA-RAMAN, SMF+EDFA-RAMAN +DCF are used instead of fiber link. EDFA-RAMAN is found to have the best performance among the three types

Munish Patial, Harpreet Kaur and Surinder Singh [31] discussed the 16 channel WDM system via dispersion mitigation and various modulation formats like RZ, NRZ, CSRZ and Duobinary format. The four modulationvformats have been numerically compared for different dispersion compensation schemes i.e. pre, post and symmetrical compensation. Symmetrical compensation has best performance in terms of Q-factor over other schemes to obtain error free transmission over longer distance as dispersion is reduced to large extent. Superior performance of CSRZ has been observed with large Q-factor.

Farah Diana and Abu Sahmah [32] investigate the comparative performances of the three most popular SOA wavelength conversion techniques; cross-gain modulation (XGM), cross-phase modulation (XPM) and four-wave mixing (FWM). The FWM wavelength converter is analyzed for two types of source; a CW and a novel spectrum-sliced source. All performances are analyzed in terms of shifted wavelength conversion efficiency, Q-factors and converted signal powers. It was found that XGM yields the highest conversion efficiency.

Farah Diana and Abu Sahmah [33] investigate the four wave mixing effect in semiconductor optical amplifier for future all optical wavelength conversion. The analysis was done by varying the wavelength shift and the power of the probe signal. The conversion efficiency, converted signal power and converted OSNR have been analyzed. It was found that the greater the conversion bandwidth, the lower was the power gained by the converted signal. Furthermore, both the conversion efficiency and converted OSNR decreased at large detuning wavelengths, due to the frequency response of the nonlinear process. Also, higher total SOA input powers were shown to increase saturation and therefore decrease conversion efficiency, while steadily increasing the OSNR.

Jameel Ahmed and Ashiq Hussain [34] analysed four wave mixing effect in dense wavelength division multiplexing system. WDM (Wavelength Division Multiplexing), on one side, produce compensation of increasing traffic and channel capacity, but on other side, pertinently caused WDM systems to undergo different linear and non-linear effects thereby degrading the performance as such. To overcome linear effects is relatively convenient and manageable, however, the non-linear effects including four wave mixing (FWM) is not only difficult to eliminate but also highly incompatible from system point of view. Therefore valid parameters which lead to generation and enhancement of FWM, are discussed, simulated and based on exhaustive sets of obtained results, a detailed analysis has been carried out to reduce the FWM.

CHAPTER 3

Nonlinearities

Fiber optic communication system considered as band limited linear system i.e it operates at moderate power level of mW and bit rate of 2.5 Gbps. Hence non linear effects don't appear in the system. If bit rate is greater than 10 Gbit/sec and transmitted power level is high then non linear effects come into picture. These need to be considered while designing a fiber. Non linearities in fiber may lead to attenuation, distortion and cross channel interference. Due to increase in optical fiber data rate, power level, number of wavelengths non linearity increases. Non linear effects have significant impact on the performance of wavelength division multiplexing system.

3.1 Causes of Nonlinearities

Fiber nonlinearities arise from two basic mechanisms. The most detrimental mechanism arises from the refractive index of glass being dependent on the optical power going through the Material. The general equation for the refractive index of the core in an optical fiber is: $n = n_0 + n_2 * P / A_{eff}$, where: n_0 = the refractive index of the fiber core at low optical power levels, n_2 = the nonlinear refractive index coefficient. P = the optical power in watts. A_{eff} = the effective area of the fiber core in square meter. The equation shows that minimizing the amount of power, P , launched and maximizing the effective area of the fiber, A_{eff} eliminates the nonlinearities produced by refractive index power dependence. Minimizing the power goes against the current approach to eliminating the detrimental effects; however, maximizing the effective area remains the most common approach in the latest fiber design.

3.2 Basics of Non Linearity

For intense electromagnetic interference device is very sensitive and at this field medium is non linear. There is harmonic motion in electrons. This motion polarization is obtained by general expression such as:

$$P = \epsilon_0 \epsilon'' E^2 + \epsilon_0 \epsilon''' E^3 + \epsilon_0 \epsilon^{(4)} E^4 + \dots \quad (3.1)$$

Where $\hat{\epsilon}$, $\hat{\chi}^1$ and $\hat{\chi}^2$ is first order susceptibility, second order susceptibility and third order susceptibility respectively. For symmetric molecules $\hat{\chi}^1$ is vanishing. For magnetic and electric dipole second order non linear effect is weak hence it is clear to say that in this type of optical fiber second order non linear effect is impossible. Lowest order non linear effect occurs in third order susceptibility.

$$E = E_0 \cos(\omega t - kz) \quad (3.2)$$

Using trigonometric formulas P becomes

$$P = \frac{1}{2} \hat{\chi}^1 E_0^2 \cos(2\omega t - 2kz) + \frac{1}{2} \hat{\chi}^2 E_0^3 \cos(3\omega t - 3kz) + \dots \quad (3.3)$$

ω is known as fundamental harmonics of polarization. 2ω is second order harmonics of polarization, 3ω is third order harmonics of polarization. $\hat{\chi}^1$ vanishes then equation 3.3 becomes:

$$P = \frac{1}{2} \hat{\chi}^2 E_0^3 \cos(3\omega t - 3kz) + \dots \quad (3.4)$$

The term 1 is linear in and term 2 is non linear in equation 3.4. Intensity (I) is defined as:

$$I = \frac{1}{2} \epsilon_0 c E_0^2 \quad (3.5)$$

From equation 3.5, equation 3.4 becomes

$$P = \frac{1}{2} \hat{\chi}^2 E_0^3 \cos(3\omega t - 3kz) + \dots \quad (3.6)$$

Effective susceptibility is

$$\hat{\chi}_{\text{eff}} = \frac{1}{2} \hat{\chi}^2 = \frac{1}{2} + 4\pi |E(\omega)|^2 \hat{\chi}^3 \quad (3.7)$$

Put equation (3.5) into equation (3.7)

$$n_{\text{eff}} = n_1 + \frac{n_2 - n_1}{1 + \frac{2(n_2 - n_1)}{n_1} I} I \quad (3.8)$$

Effective refractive index is

$$n_{\text{eff}} = 1 + 4\pi \chi_{\text{eff}} \quad (3.9)$$

Put equation (3.8) into equation (3.9)

$$n_{\text{eff}} = n_1 + \frac{n_2 - n_1}{1 + \frac{2(n_2 - n_1)}{n_1} I} I \quad (3.10)$$

$$n_{\text{eff}} = n_1 + n_2 I \quad (3.11)$$

$$n_{\text{eff}} = n_1 + \frac{n_2 - n_1}{1 + \frac{2(n_2 - n_1)}{n_1} I} I \quad (3.12)$$

For fused silica $n_1 = 1.46$ and $n_2 = 3.2 \cdot 10^{-20}$

The change in refractive index is $\Delta n = n_2 I$

3.3 Types of Non-linearities

Single channel	Multichannel
Self-phase modulation (SPM) Signal optical phase modulated proportionally to signal power; conversion to intensity «noise» by GVD	Cross-phase modulation (XPM) Signal optical phase modulated Proportionally to power of neighboring conversion to intensity «noise» by GVD.

<p>Modulation instability (MI)</p> <p>When two continuous waves travel with different velocity</p> <p>Selective amplification of noise</p>	<p>Four-wave mixing (FWM)</p> <p>Generation of new spectral components;</p> <p>Crosstalk when overlap with other channels.</p>
<p>Stimulated Brillouin scattering (SBS)</p> <p>Retro diffusion of energy;</p> <p>Increases fiber loss.</p>	<p>Stimulated Raman scattering (SRS)</p> <p>Energy transfer from lower-wavelength channels to higher-wavelength ones</p>

Table 1 : Types of non linearities

In optical fiber the refractive index depends on optical intensity of signal propagating through the fiber. Thus phase of light at the receiver depends upon the phase of light at the transmitter, length of fiber and optical intensity. Self phase modulation (SPM) and cross phase modulation (CPM) are caused by this phenomenon.

3.3.1 Self Phase Modulation: it is caused by variation in power of optical signal and results in variation of the phase of signal. The amount of phase shift introduced by self phase modulation is given by:

$$\phi_{N.L} = n_2 K_0 L |E|^2 \quad (a)$$

Where n_2 is non linear index of refraction, $K_0 = \frac{2\pi}{\lambda}$, L is length of fiber and $|E|^2$ is optical intensity. In PSK systems, self phase modulation may lead to degrade of system performance, since receiver realize on phase information. Self phase modulation also leads to spectral broadening of pulses. If there is instantaneous change in phase of signal, it will result in change of frequency around the signal's central frequency. SPM modifies only phase shift which varies with time, in SPM spectrum is changes when pulse propagating through fiber. The frequency spectrum (ω) is:

$$\omega = \frac{\partial \phi}{\partial t} \quad (b)$$

In dispersive medium, the new instantaneous frequency becomes:

$$\omega' = \omega_0 + \frac{\partial \phi}{\partial t} \quad (c)$$

Effective refractive index is defined as: $n_{\text{eff}} = n_1 + n_2 I$ (d)

Put equation (d) in equation (a) and $L_{\text{eff}} = L$

$$\phi = \frac{\pi}{\lambda} (n_1 + n_2 I) L_{\text{eff}} \quad (e)$$

From above equation it is clear that ϕ depends upon I , phase shift in SPM is negative so equation (c) becomes:

$$\omega' = \omega_0 - \frac{\partial \phi}{\partial t} (n_1 + n_2 I) L_{\text{eff}} \quad (f)$$

The leading edge of pulse $\frac{\partial I}{\partial t} > 0$ then

$$\omega' = \omega_0 - \omega(t) \quad (g)$$

The trailing edge of pulse $\frac{\partial I}{\partial t} < 0$ then

$$\omega' = \omega_0 + \omega(t) \quad (h)$$

The leading or trailing edge of pulse leads to pulse chirped this type of chirping results to spectral broadening. The size of frequency increases when time I is varied hence pulse spreading occurs. This type of spreading is called dispersion. SPM changes phase only, the changed phase depends upon its own pulse shape. SPM produces ultra-short pulses at high repetition rate and it degrades the performance of light wave system. Modulation instability produces noise. It is defined as when two continuous waves travel with different velocity.

Applications:

- Pulse compression, optical switching, passive mode locking, pulse compression, all optical regeneration for WDM channel.

Mitigation Strategies:

- Lowering the optical power at the expense of increased noise
- Dispersion management, because dispersion can partly mitigate the SPM effect

3.2.2 Cross Phase Modulation: SPM limit to single channel but XPM uses two channels. It is shift in phase of signal, caused by change in intensity of signal propagating at different wavelength. Cross phase modulation leads to asymmetrical broadening of pulses and combined with dispersion may also affect pulse shape in time domain. Although cross phase modulation limit the performance of fiber optic system, it has advantages also i.e. cross phase modulation can be used to modulate a pump signal at one wavelength from a modulated signal on a different wavelength.

Advantages:

- Demultiplexing of OTDM channel
- Wavelength conversion of WDM channel
- Passive mode locking
- Ultra fast switching: long fiber and mach-zehnder is used for switching, switching time is greater than 1 ps.
- Nonlinear pulse compression

Disadvantages:

- Produce timing jitter and amplitude
- Inter- channel cross talk

Cross Phase Modulation is degrading the performance of system more than self phase modulation. For larger channel cross phase modulation adversely affect the system.

3.2.3 Four Wave Mixing (FWM): in WDM system. If three waves with angular frequency f_i , f_j , and f_k propagate in fiber the non-linear susceptibility of silica fiber produces a new wave at angular frequency of: $f_i \pm f_j \pm f_k$

Because of phase matching condition the frequency $f_i + f_j - f_k$ are most troublesome for WDM system. For N wavelength channels co-propagating through fiber, number of frequencies generated by this is: $M = N^2 \left(\frac{???}{?} \right)$

Interaction between two frequencies produces two extra frequencies as shown in figure 3.2



Figure 3.1: f_1 and f_2 put inside the fiber



Figure 3.2: Generation of Side bands

Methods to reduce Four Wave Mixing:

(a) **Uneven channel spacing:** the positions of channels can be chosen carefully so that the Frequencies due to FWM do not overlap with data channels inside the receiver bandwidth. This may be positive for small no. of channels in some cases but

needs careful computation of the exact channel positions.

(b) Increasing channel spacing: this increases group velocity mismatch between the channels. This has drawback of increasing the overall system bandwidth, requiring the optical amplifier to be flat over a wider bandwidth, and increases the penalty due to SRS.

(c) Minimum launching power

(d) Optical phase conjugation method: The data signal at frequency ω_{signal} is coupled together with a pump signal at frequency ω_{pump} and afterwards fed in an OPC medium. At the output of the OPC unit, a conjugate signal is presented at a different wavelength ω_{conj} . OPC reverses the order of the spectrum and translates the spectrum to some high value at which the dispersion is Nonzero that could suppress the FWM effect. The output signal of OPC is called as conjugated signal. The concept of OPC is shown in Fig 3.3.

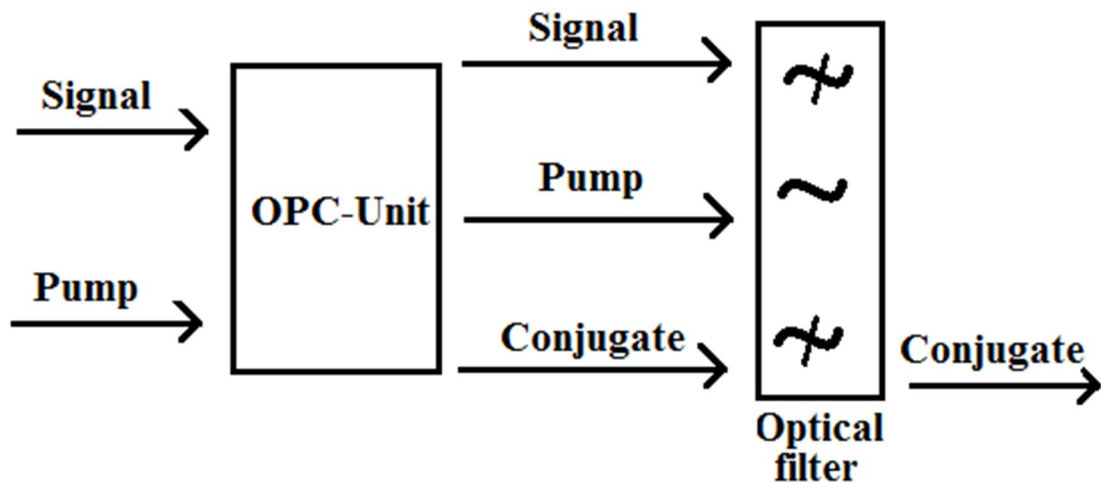


Figure 3.3: Optical phase conjugation method

Here the optical signal at the wavelength sig and pump signal at the wavelength pump are given as input to the OPC unit. Then optical signal and the pump signal are mixed together in OPC medium and produce the conjugated signal at the wavelength conj.

$$\omega_{\text{conj}} = \omega_{\text{pump}} - \omega_{\text{sig}}$$

Output of the OPC unit is passed through the optical filter. Both optical signal and pump signal are filtered. Conjugated signal is allowed to pass through the Filter. OPC does not attenuate the signal. OPC is placed in the midway of the fiber optic link. This arrangement of OPC can effectively reduce the fiber non linear effects. Another OPC is inserted after the second half of the fiber in order to get a signal at the original wavelength. Here the conjugate signal and the same pump wavelength is given as input to the OPC2 then we get output of OPC2 as input of the OPC1 with reduced non linear effects.

3.2.3 Stimulated Raman scattering (SRS): it is caused by interaction of light with molecular vibrations. SRS is result of inelastic scattering of light wave propagating through silica optical fiber by silica molecules. Initially $E_1=h\nu_1$ when photon of light interacts with silica molecules, some of energy is absorbed and photon gets scattered. As the original photon has lost energy so new energy becomes $E_2=h\nu_2$. If ν_1 is greater than ν_2 then $\nu_1 - \nu_2 = \Delta\nu$. This change in frequency of two interactive photons from ν_1 to ν_2 is stokes shift. SRS causes transfer of power from shorter wavelength to longer wavelength.

Consider WDM system with M equally spaced channels with channel spacing $\Delta\nu_s$. Let same power is transferred in all the channels and there is no interaction between different channels. The fraction of power coupled from channel 0 to channel i is given by:

$$P(i) = (g_R) i \frac{\Delta\nu_s \cdot A_{eff}}{\Delta\nu_s \cdot A_{eff}}$$

Where g_R is Raman gain coefficient, $\Delta\nu_s$ is total channel spacing, A_{eff} is effective area.

The fraction of power coupled from 0 to all channels is $P = \frac{\Delta\nu_s \cdot A_{eff}}{\Delta\nu_s \cdot A_{eff}}$

$$\text{Then } P = \frac{\Delta\nu_s \cdot A_{eff}}{\Delta\nu_s \cdot A_{eff}} \cdot \frac{\Delta\nu_s \cdot A_{eff}}{\Delta\nu_s \cdot A_{eff}}$$

$$P = (g_R) i \frac{\Delta\nu_s \cdot A_{eff}}{\Delta\nu_s \cdot A_{eff}} \cdot \frac{\Delta\nu_s \cdot A_{eff}}{\Delta\nu_s \cdot A_{eff}}$$

Applications of SRS

- Raman fiber Laser
- Raman fiber amplifier
- Eye safe laser

Mitigation of SRS:

- The transmitting power level in each channel should be below a threshold value.
- Distance between optical amplifiers should be reduced
- SRS cause problem if the system has large number of wavelengths.
- Channel spacing should be less

3.2.4 Stimulated Brillouin scattering (SBS): it is similar to Stimulated Raman Scattering except that the frequency shift is caused by sound wave rather than molecular vibrations. In SBS scattering of pump wave occurs in sound wave. This process creates a stoke wave in backward direction and at lower frequency. Thermal generation in medium is responsible for scattering of light. Light is scattered from non propagating components. The energy is transmitted back when transmitting energy is greater than threshold power. Threshold power is defined as at which non linear effect occurs. For SBS, threshold power is approximately 1mw. When SBS is lower than threshold power, the transmitted power linearly increases. At larger intensity SBS occurs. For high speed transmission it is necessary to control stimulated Brillouin scattering. The SBS does not create interaction with different wavelengths until wavelength spacing is much greater than 20MHz. it can cause interference if the amplitude of scattering signal is greater than input signal. The frequency shift due to SBS is given by:

$$V_B = 2n \frac{v_a}{\lambda_p}$$

Where V_a is velocity of acoustic wave, n is mode index of fiber and λ_p is pump wavelength. The intensity of SBS is much larger than SRS but the frequency range of SBS is much smaller than SRS.

Applications of SBS:

- Pipelining bucking detection
- Beam combiner
- Fiber sensor
- Pulse delaying and advancement

CHAPTER 4

PROPOSED WORK

This chapter simulates eight channel WDM optical communication system to investigate the effect of channel spacing, effect of data rate, number of channel, fiber length and the effect of dispersion. The combination of four parameters i.e. decreasing the input power, increasing the effective area, increasing the channel spacing and increasing the fiber length gives the best reduction on the FWM power.

4.1 Introduction:

Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. In Dense Wavelength Division Multiplexing (DWDM) multiple channels of information can carry over a single fiber each using an individual wavelength. In DWDM the channels are closely spaced and the channel spacing is reduced as 1.6nm. In DWDM system, the optical fiber under high data rates suffers from some of the undesirable effects that affects the system efficiency and degrade the system performance. FWM is a non-linearity which degrades the system performance. When two or more signals travel in a fiber, interaction between the wavelengths generates a new signal. The FWM power generated at the end of the fiber due to interaction of channels at frequencies, f_i, f_j, f_k is given by:

$$P_{FWM} = \left(\frac{1024 \pi^6}{n^4 \omega^2 c^2} \right) (DX)^2 \left(\frac{P_i P_j P_k}{A_{eff}^2} \right) (L_{eff})^2 \eta \dots$$

Where P_i, P_j, P_k are input powers in optical fiber at frequencies f_i, f_j, f_k respectively. ω is zero dispersion wavelength, n is refractive index of fiber, c is the velocity of light, X is third order non linearity susceptibility, A_{eff} is the effective area of fiber, L_{eff} is effective length of fiber, α is fiber attenuation coefficient and D is degenerative factor where $D=6$ for $i=j$ and $D=3$ for $i \neq j$. The FWM product is increased by increasing the input power. When new frequencies fall and overlap the original frequency, it causes sharp crosstalk between channels passing through an optical fiber. Degradation becomes very severe when the number of WDM channels increase and have small spacing. Several techniques

have been used to suppress the effect of FWM crosstalk and enhance the signal output. Four Wave Mixing can be reduced by using unequal channel spacing, decreasing the input power, decreasing number of channels, increasing the channel spacing.

4.2 Schematic Model:

The Schematic model is the general set up for an optical communication system as shown in figure 4.1, in which optical fiber is installed which adds non linearities like FWM (four wave mixing). The pre amplifier, post amplifier and in line amplifier are used for long distance communication. The transmitter section consists of a laser, modulator driver, pn-sequence generator i.e. data source and modulator. The wavelength of various channels is set by keeping the difference equal to the spacing required. Then all these transmitted signals are combined /multiplexed together. Then the combined signal is amplified so that it can be transmitted over long distances without its degradation. Then the signal is transmitted over the nonlinear fiber which adds the nonlinearities into the signal. At the receiver side, the signal is demultiplexed. The receiver consists of a photodiode and a low pass filter.

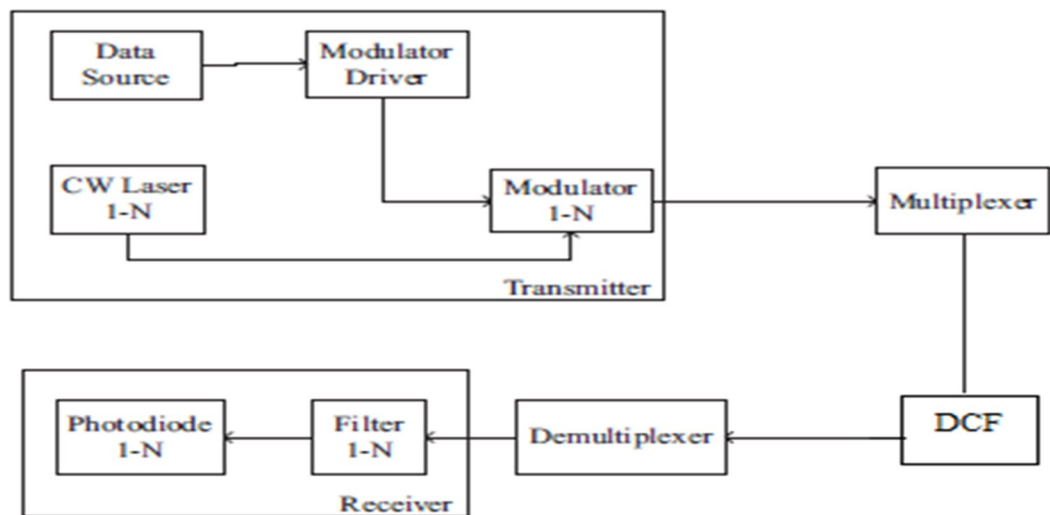


Figure 4.1: Schematic Model

4.3 Simulation Set up

Fig. 4.2 shows system setup for eight-channel 120 Gbps DWDM transmission link. The optical transmitter consists of 8 continuous wave Semiconductor laser sources to create

the carrier signal. The data Sources d1 to d8 is externally modulated by D1 to D8 modulator drivers respectively. PRBS generator generates pseudo random bit sequence at the bit rate of 15Gbps with $2^7 - 1$ bits. This bit sequence is fed to RZ pulse generator to generate RZ sequence. Modulator driver decides the input data format. The RZ cosine data format is used here. The modulated data from M1 to M8 is combined in multiplexer/combiner. To evade losses from fiber post amplifier is used. After amplification signal goes to optical fiber. Then non linear effects, dispersion and attenuation are activated. Then Dispersion Compensation Fiber (DCF) is used to neglect the dispersion and to introduce phase mismatching in the signals. Then In line amplifier is used to amplify the signal. Then again signal goes through fiber and dispersion compensating fiber. Then pre amplifier is used before the splitter/demultiplexer. Splitter split the signals into the same number of signals as they were combined. Then optical to electrical conversion is done using photodiode. BER analyzer is used to estimate the BER and Q factor. Then signal is passed through low pass filter and final result is obtained.

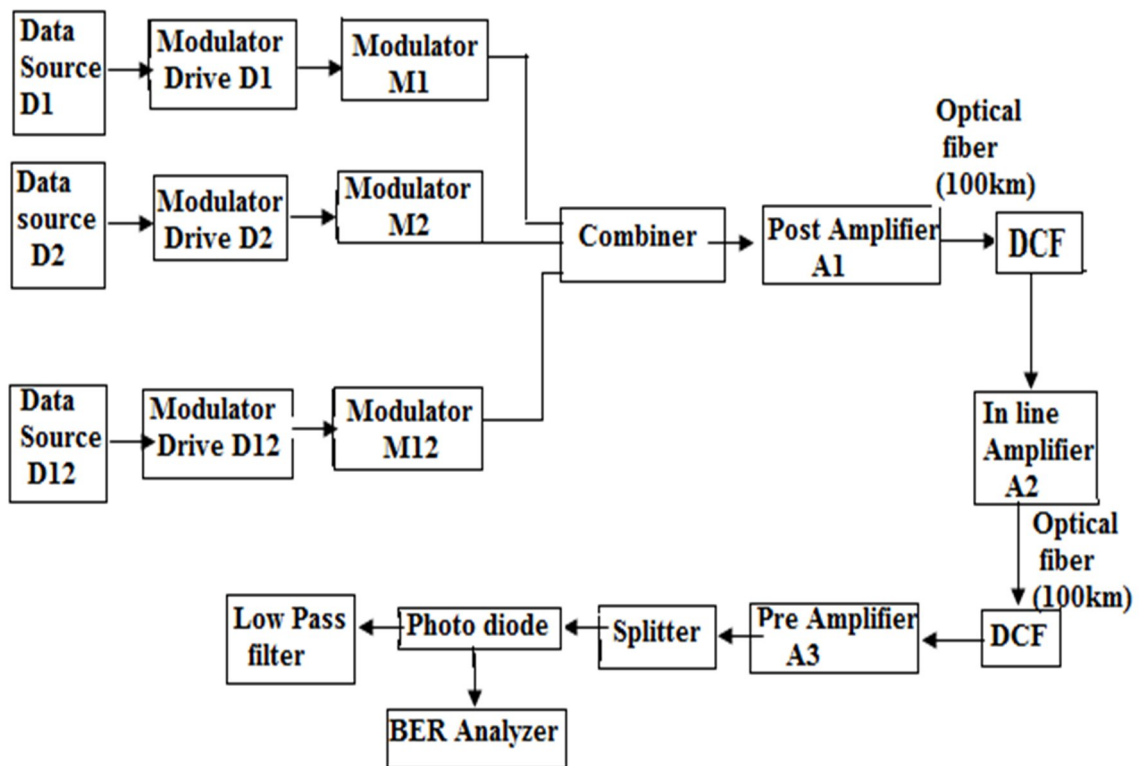


Figure 4.2: Simulation set up

4.4 Methodology

Case-1: Fiber Length

Increasing the fiber length reduces the four wave mixing power. Fig 4.3 shows the FWM power is reduces to -84 dbm when length of fiber is 150 km while FWM power is -52dbm at 10km.

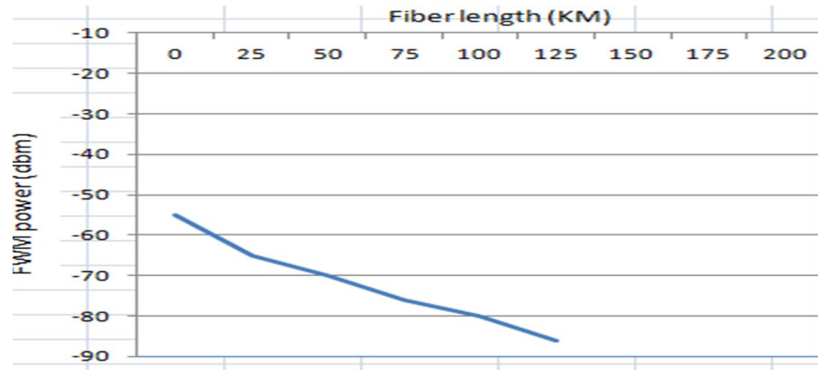


Figure 4.3: FWM Power against fiber length

Case-2: Input Power

Decreasing the input power reduces the four wave mixing Power. Fig 4.4 shows FWM power is reduces to -86 dbm when input power is -5 dbm while FWM power is -48 dbm at 10 dbm power.

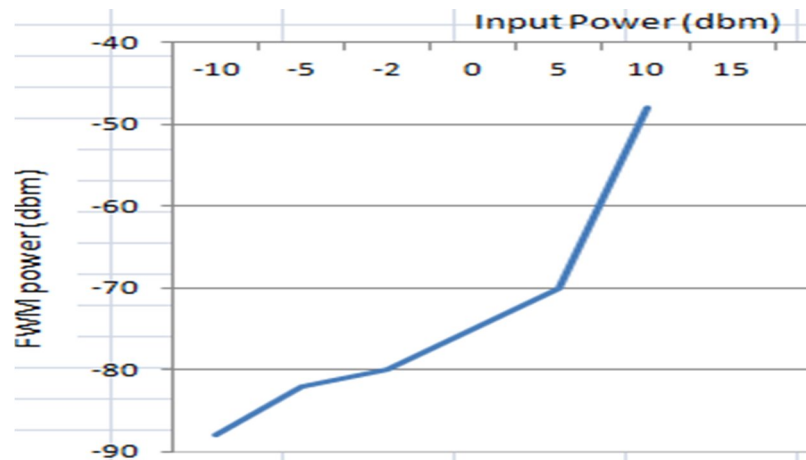


Figure 4.4: FWM Power against input Power

Case-3: Effective Area

Increasing the effective area decreases the four wave mixing power because effective area is inversely proportional to input power. Fig 4.5 shows FWM power is reduces to -82 dbm when effective area is 80 μm^2 while FWM power is -70 dbm at 45 μm^2 .

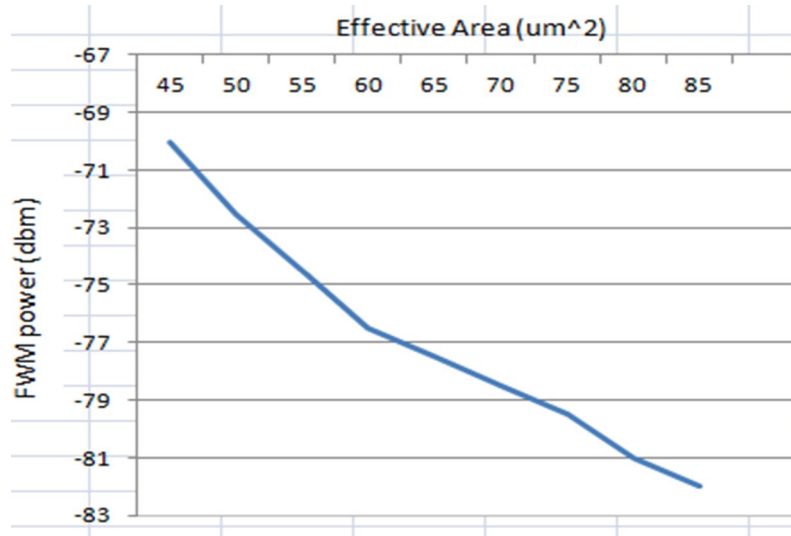


Figure 4.5: FWM Power against effective Area

Case-4: Combined effect of Input power and Fiber Length

Decreasing the input power and increasing the fiber length can reduce the four wave mixing power. Fig 4.6 shows FWM power is reduces to -56 dbm at fiber length of 25 Km and input power of 0.08 W while FWM power is -22 dbm at fiber length of 10 km and input power of 0.08W.

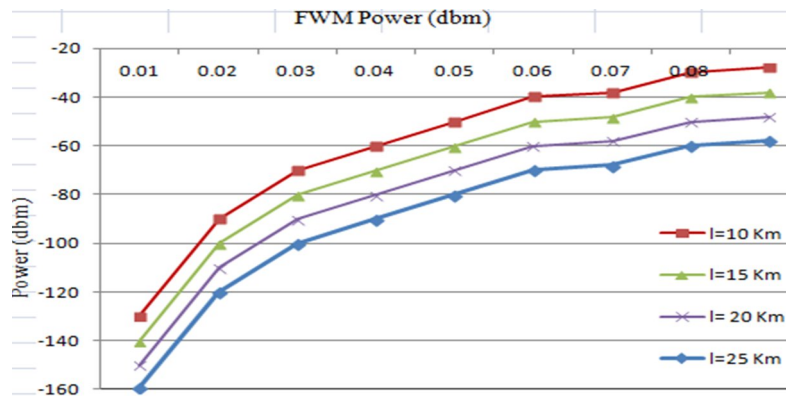


Figure 4.6: FWM against input Power for different length of fiber

Case-5: Combined effect of Input Power, Fiber length and Channel Spacing

Figure 4.7 shows FWM power is reduces to -70 dbm at fiber length of 25 km and input power 0.08 W with increased Channel spacing while FWM power is -37 dbm at 10 km. As compared to case 3 FWM power is reduces to -70 dbm from -56 dbm. Therefore combined effect of decreasing input power, increasing channel spacing and fiber length reduces FWM power from 4% to 12%.

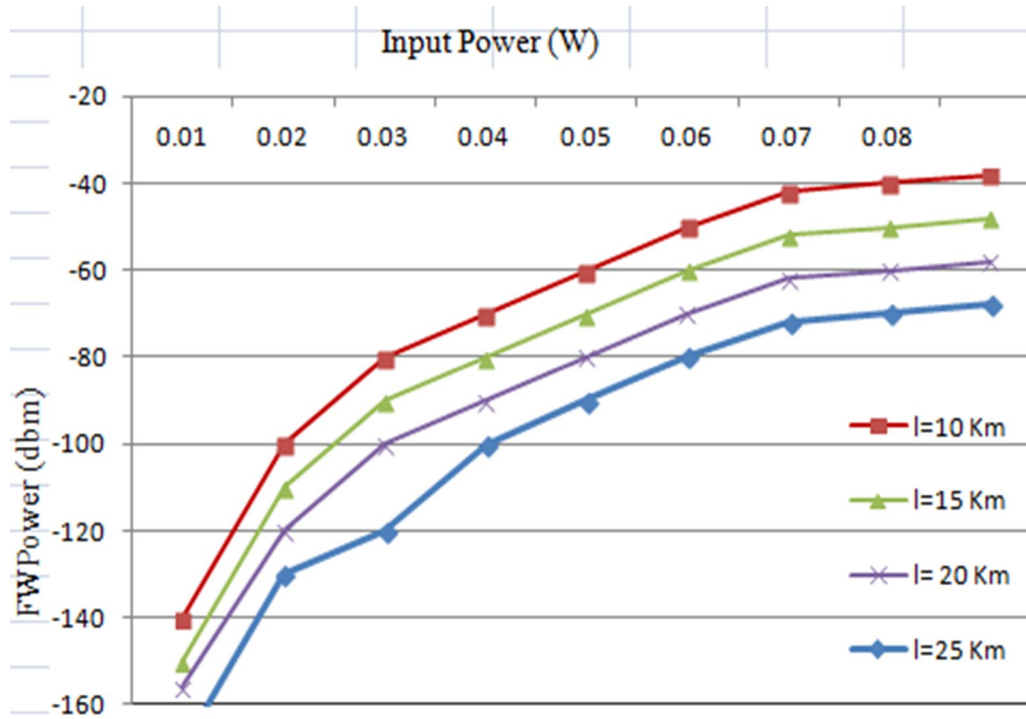


Figure 4.7: FWM Power against input power for different Length of fibers with increased channel spacing

4.5 Results and Discussion

Simulation software Optisystem 13.0 is used to evaluate and compare the performance of the proposed DWDM system in the presence of Four Wave Mixing under the impact different parameters. The performance of system is measured by measuring Q factor and BER using BER analyzer at the receiver. As shown in figure 4.8 Q factor decrease as fiber length increases. Figure 4.8 shows with increase in input power Q factor decrease. But Q factor increase with large channel spacing. Figure 4.9 shows the variation of Q factor with input channel spacing. Q factor decreases as channel spacing decreases and

increases with increasing channel spacing. As shown Q factor is maximum at channel spacing of 100 GHz and minimum at channel spacing of 25 GHz.

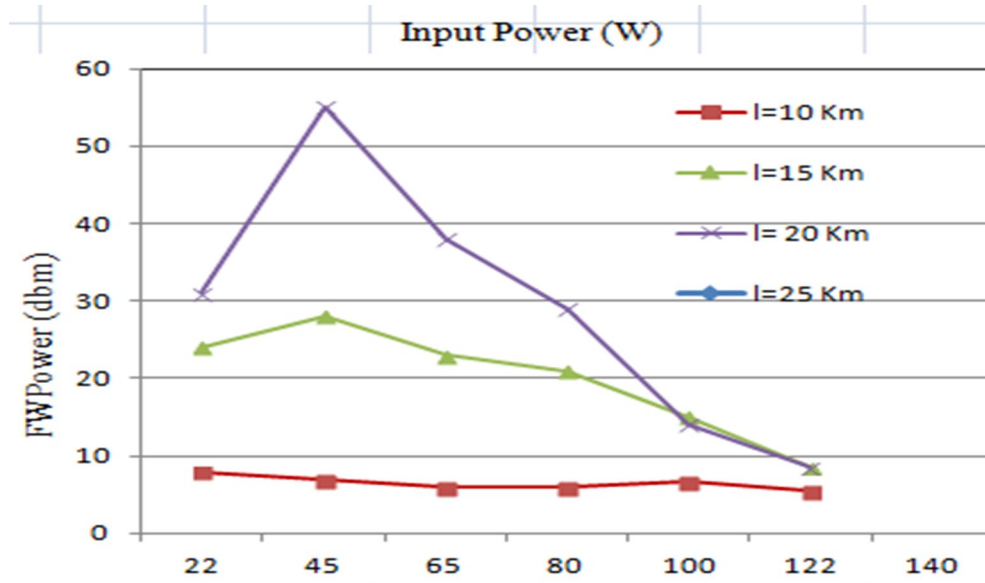


Figure 4.8: Comparison of Q factor and Fiber length for different channel spacing

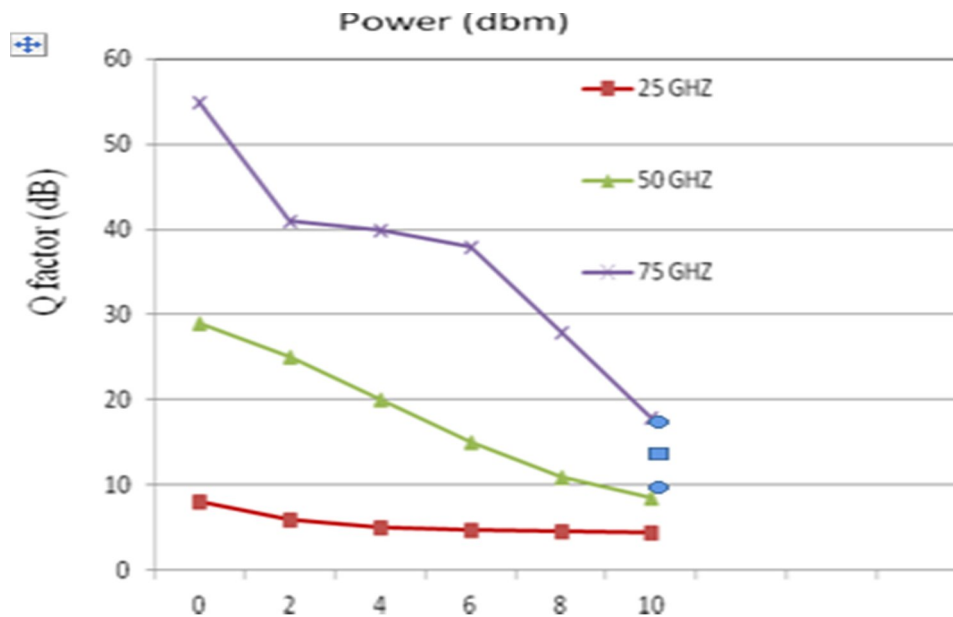


Figure 4.9: Comparison of Q factor and input Power for different channel spacing

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

Conclusion

Single and combined effect of various parameter such as fiber length effective area, input power and channel spacing have been analyzed to determine the effectiveness of FWM power. DWDM system with 120Gbps is implemented in the presence FWM to calculate and compare the BER, Q-factor and FWM power.

Decreasing the BER and increasing the Q factor, decreases the four wave mixing effect and increases the system performance. It is interesting to note that increasing the fiber length + effective area + channel spacing + decreasing the input power is the optimum approach to reduce the effect of four wave mixing power to lowest value. FWM power is reduced to 20% as compared to individual parameters.

Future Scope:

In this thesis, the work is done on the effect of four wave mixing in DWDM system. The non linear effects stimulated Raman scattering and stimulated Brillouin Scattering are not included. The effect of changing various parameters like channel spacing, fiber length, effective area is studied on these non linear effects.

Analysis of FWM effect has been done on different modulation formats such as NRZ, RZ and Manchester, further study could be done on CSRZ (carrier suppressed RZ)

The simulation results for 16 × 10 Gbps in the presence of hybrid modules can be enhanced further in the term of number of channels, data rate, channel spacing etc.

REFERENCES

- [1] G.P. Aggarwal, “Fiber Optic Communication Systems”, *Wiley, New York*, 1997.
- [2] M Arumugam, “Optical fiber communication-An overview”, *PRAMANA journal of physics*, Vol.57, pp.849-869, 2001
- [3] Monika, Amit Wason, R.S. Kaler, “Investigation of four wave mixing effect with different number of input channels at various channel spacing”, *Optik – International Journal for Light and Electron Optics*, Vol. 124, pp.4227–4230, 2013
- [4] S.P. Singh and N. Singh, “Nonlinear effects in optical fibers: origin, management and applications”, *Progress in electromagnetic research*.Vol.73, pp. 249-275, 2007.
- [5] Surinder Singh, Sukhbir Singh, “Investigation on four wave mixing effect in various optical Fibers for different spectral efficient orthogonal modulation Formats”, *optics and laser technology*. Vol.76, pp 64-69, 2015
- [6] Gurpreet Kaur, M.L Singh, “Effect of four wave mixing in WDM optical fiber systems”, *Optik-International Journal for Light and Electron Optics*, Vol.120, pp 268-273, 2009
- [7] S.J.B. Yoo, “Wavelength conversion technologies for WDM network applications”, *Journal of. Lightwave Technology*, vol. 14, pp. 955–966, 1996.
- [8] Yasin M. Karfaa, M. Ismail, “Effects of Four-wave Mixing Crosstalk in WDM Networks on the Transmitted Optical Frequencies and Wavelengths of Channels for Various Fiber Types”, *Asia Pacific Conference on applied Electromagnetic Proceedings*, December, 2007
- [9] S Sugumaran, Manu Aggarwal, P Arulmozhivarman, “analysis of FWM power and efficiency in DWDM systems based on chromatic dispersion and channel spacing”, *International Journal of Advances in Engineering Research*, Vol.7,pp. 49-60, 2014

- [10] John M. Senior, *Optical Fiber Communication*, second edition, Principles and Practice, 1999
- [11] S.P. Singh, V.K. Jain, "Novel strategies for reducing FWM using modified repeated unequally spaced channel allocation", *fiber and integrated optics*, Vol.6, pp. 415-437, 2004
- [12] Gurmeet Kaur, "Optimization of inter channel Separation in WDM transmission system in the presence of Fiber Nonlinearities ", IFIP International Conference, IEEE, Vol. 24. Pp. 1-6, 2007
- [13] Vishal Sharma and Ramandeep Kaur, "implementation of DWDM system in the presence of four-wave mixing (FWM) under the impact of channel spacing", *int. j. light electron opt.*, 2012
- [14] R. S. Kaler, Anu Sheetal, Ajay K. Sharma "Impact of Optical Modulation Formats on SPM-limited Fiber Transmission in 10 and 40 Gb/s Optimum Dispersion-managed Lightwave Systems" *Optik*, Vol. 121, 2010
- [15] Bing Yao, Masansor Hanawa and Miko Takahara, "wavelength division multiplexing transmission based on wide-band optical phase conjugator using dispersion flat fiber", *Optik.*, pp. 313–316, 2011.
- [16] S. Pachnicke, E. De Man, S. Spälter, and E. Voges, "Impact of the In-Line Dispersion-Compensation Map on Four-Wave Mixing (FWM) – Impaired Optical Networks," *IEEE Photonics Technology Letters*, Vol. 17, No. 1, pp. 235-237, January 2005.
- [17] P. L. Li, D. X. Huang, X. L. Zhang, J. Chen, and L. R. Huang, "Theoretical Analysis of Tunable Wavelength Conversion Based on FWM in a Semiconductor Fiber Ring Laser," *IEEE Journal of quantum electronics*, Vol. 41, pp. 581-588, March 2005

- [18] I.Rasheed, M Abdullah, Shahid Mehmood, ,” Analyzing the Non-linear Effects at various Power Levels and Channel Counts on the Performance of DWDM based Optical Fiber Communication System”, *IEEE journal of quantum electronics*, pp 7-12, 2012
- [19] Borja Vidal, *Member@IEEE*, Alexander Bockelt,”Cascaded Four-Wave Mixing for Microwave Photonic Harmonic Multiplication”,*IEEE photonic technology letters*, Vol 25,pp100-103, 2013
- [20] Qiang Hao, Heping Zeng,” Cascaded Four-Wave Mixing in Nonlinear Yb-Doped Fiber Amplifiers”, *IEEE journal of quantum electronics*,Vol 20,October 2014
- [21] Amarpal Singh, Ajay K. Sharma,” Investigation on modified FWM suppression methods in DWDM optical communication system”, *optic communication*, Vol. 282 pp. 392-395
- [22] Jameel Ahmed, Ashiq Hussain, M.Y. Siyal,” Parametric analysis of four wave mixing in DWDM systems” *optik*, Vol 125, pp 1853-1859, 2014
- [23] H.J. Abed, N.M. Din, M.H. Al-Mansoori, ” Recent four-wave mixing suppression methods”, *Optik*, Vol 124, pp 2214-2218, 2013
- [24] M. Noshad, A. Rostami,” FWM minimization in WDM optical communication systems using the asymmetrical dispersion-managed fibers”, *Optik* Vol 123, pp 758-760, 2012
- [25] Rajneesh Kaler, R.S. Kaler, ”Investigation of four wave mixing effect at different channel spacing”, *Optik*, Vol 123,pp 352-356, 2012
- [26] Gurpreet Kaur , M.S Patterh,” Suppression of four wave mixing in wavelength division multiplexed system with hybrid modules”, *Optik*, Vol 125, pp 3894-3896, 2014

- [27] T. Sabapathi, G.Jaya Brindha,” Mitigation of Fiber Non Linear Effects by Maximum Likelihood Sequence Detection”, *International Conference on communication and Network Technologies*, Vol 14, pp154-157, 2014
- [28] C. T. Politi, D. Klonidis, and M. J. O’Mahony, “Dynamic Behavior of Wavelength Converters based on FWM in SOAs,” *IEEE journal of quantum electronics*, Vol. 42, No. 2, pp. 108-125, February 2006.
- [29] I.B. Djordjevic, “Transmission Limitation of WDM transmission systems with Dispersion compensating Links in the presence of Fiber Nonlinearities”, *Proceeding TELSIS, IEEE, Nis, Yugoslavia*, vol. 21,pp. 496-499, 2001
- [30] A. Nandhini and K. Gokulakrishnan,” Design of Ultra High Capacity DWDM System with Different Modulation Formats", *International Journal of Engineering and Industrial Applications*, Vol.3, pp 41-45, 2014
- [31] Munish Patial, Harpreet Kaur and Surinder Singh,” Performance Analysis of 16 Channel WDM System via Dispersion Mitigation and Various Modulation Formats”, *International Journal of Engineering Research & Technology (IJERT)*, Vol. 3,pp 57-60, 2014
- [32] Farah Diana and Abu Sahrh,” Analyses of semiconductor optical amplifier (SOA) four-wave mixing (FWM) for future all-optical wavelength conversion”, *Optik*, Vol. 124, pp 1-3, 2013

LIST OF PUBLICATIONS

1. Research paper titled “Comparative Performance Analysis of FWM Effect in DWDM System”, published in International Journal of Advance Research in Education & Technology (IJARET), April-June 2016

margin_with_page_number.docx

ORIGINALITY REPORT

24%

SIMILARITY INDEX

24%

INTERNET SOURCES

0%

PUBLICATIONS

0%

STUDENT PAPERS

PRIMARY SOURCES

1	dspace.unimap.edu.my Internet Source	2%
2	www.ajayksharma.com Internet Source	2%
3	dspace.thapar.edu:8080 Internet Source	2%
4	deron.csie.ncue.edu.tw Internet Source	2%
5	research.ijcaonline.org Internet Source	1%
6	ijarcce.com Internet Source	1%
7	riunet.upv.es Internet Source	1%
8	www.patra.com Internet Source	1%
9	www.ginque.com Internet Source	1%
