Performance Analysis of Nonlinearities in Optical Fibers

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

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CERTIFICATE

I, PriyankaDalotra, hereby certify that the work which is being presented in this thesis entitled "**Performance Analysis of Nonlinearities in Optical Fibers**" by me in partial fulfillment of the requirements for the award of degree of Master of Engineering in Electronics and Communication Engineering from Thapar University (Deemed University), Patiala, is an authentic record of my own work carried out under the supervision of Dr.Hardeep Singh

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It is certified that the above statement made by the student is correct to the best of our knowledge and belief.

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ABSTRACT

Non linearity effects arose as optical fiber data rates, transmission lengths, number of wavelengths and optical power levels increased. The only worries that plagued optical fiber in the early day were fiber attenuation and sometimes, fiber dispersion; however, these issues are easily dealt with using a variety of dispersion avoidance cancellation techniques. Fiber nonlinearities present a new realm of obstacles that must be overcome. The nonlinearities previously appeared in specialized applications such as undersea installations. However the new nonlinearities that need special attention when designing fiber optic system include stimulated brillouin scattering (SBS), stimulated Raman Scattering (SRS), four wave mixing (FWM), self phase modulation (SPM), cross phase modulation (XPM) and intermodulation. Fiber nonlinearities represent the fundamental limiting mechanism to the amount of data that can be transmitted on a single optic fiber. This thesis presents a study of these limitations and the steps that can be taken to minimize the effect of nonlinearities. The effect of nonlinearities at different data rates and effective length of fiber have been studied. The data rates, transmission lengths and the channel spacing have to be optimized in order to have an efficient transmission without any nonlinear effect. The non-linear effects tends to manifest themselves when optical power is very high, they become important in DWDM. FWM is one of the dominating degradation effects in WDM systems with dense channel spacing. If the channels are equally spaced, the new waves generated by FWM will fall at channel frequencies and will give rise to crosstalk. The effect of FWM at various channel spacing in WDM systems have been studied in this thesis, however the optimum channel spacing, effective length and cross-sectional area have to be found. Effect of nonlinearities and hence the choice of data format (NRZ, RZ, NRZ raised cosine, RZ raised cosine) have to be worked upon. Apart from FWM, SPM and XPM also degrade the system performance. All these nonlinearities along with chromatic dispersion have been studied. It is found that some amount of chromatic dispersion can minimize the nonlinearities. The simultaneous if compensation of dispersion and nonlinearities is presented.

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ABBREVIATIONS

WDM	Wavelength Division Multiplexing
FWM	Four Wave Mixing
LAN	Local Area Network
TDM	Time Division Multiplexing
FDM	Frequency Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
SPM	Self Phase Modulation
XPM	Cross Phase Modulation
BER	Bit Error Rate
Q-factor	Quality Factor
PSO	Pseudo Orthogonal
MAN	Metropolitan Area Network
CS-RZ	Carrier-Suppressed Return-to-
Zero DPSK	Differential Phase-Shift Keying
SMF	Single Mode Fiber
PMD	Polarization Mode Dispersion
SOA	Semiconductor Optical Amplifier
ITU-T	International Telecommunication Union-Telecommunication
NRZ	Non Return-to-Zero
RZ	Return-to-Zero
CD	chromatic dispersion
OPC	Optical phase conjugator
MSSI	Mid span spectral inversion
SRS	Stimulated Raman Scattering
SBS	Stimulated Brillouin Scattering

CHAPTER 1

INTRODUCTION

1.1 Overview

Since the mid 90's, optical fiber shave been used for point to point communication at a very high speed. Fiber-optic is a method of transmitting information from one place to another by sending light through an optical fiber. Fiber-optic communication systems have played a major role in the advent of the information age. The speed offered by optical fibers is much higher than the speed of electronic signal processing at both ends of the fiber. Optical fibers have largely replaced copper wire communications because of its advantages over electrical transmission. The advantages of optical fiber include its inherently high data carrying capacity, such that thousands of electrical links would be required to replace a single high bandwidth and its low loss, allowing long distance between amplifiers or repeaters. Another benefit of fiber is that even when run alongside each other for long distances, fiber cables experience effectively no crosstalk, in contrast to some types of electrical transmission lines. Fibers offer high speed, large capacity and high reliability by the use of its huge bandwidth. One of the basic concepts in fiber optic communication is the idea of allowing several users to transmit data simultaneously over the communication channel by simultaneously allocating the available bandwidth to each user. This concept is known as multiple access. There are two types of multiple access techniques: Asynchronous and Synchronous. Asynchronous multiple access methods, where network access is random and collisions occur are well suited to LAN's with low traffic demand [1]. However, these asynchronous access methods suffer from cumulative delay as the traffic intensity increases. On the other hand, synchronous accessing methods, where transmissions are perfectly scheduled provide more successful transmissions than asynchronous methods [2].

1.2 Multiplexing

Since the first wires were laid for telegraphs in the 1800's, the drive has been to increase the amount of information that can be sent in a given interval. In the early years of telegraphs, telephones, and other telecommunications, the simple and obvious solution was to add more lines of communication. Due to the increased cost of wire-laying and maintenance, multiplexing techniques were introduced in which more than one signal is sent over the same line [3].

1.3 Types of multiplexing techniques

The commonly used multiplexing techniques are TDM, FDM and WDM.

(a) Time division multiplexing (TDM): Time division multiplexing (TDM) is the least efficient form of multiplexing. In TDM, multiple signals are transferred, but each one is sent in parts, as seen in the figure below:

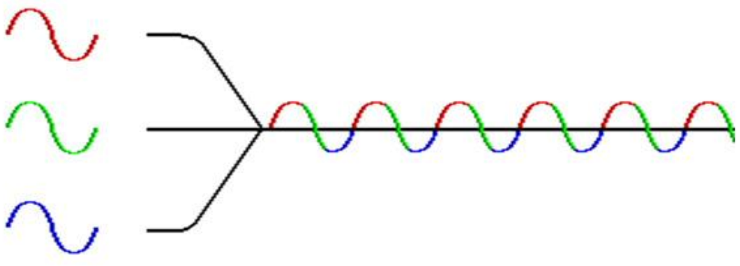


Fig.1.1 TDM [3]

It is clear in the figure that two thirds of each signal is lost due to the division of time that gives TDM its name. This form of multiplexing is uneconomical for digital information transfers, as much of the signal from each source is lost. If the number of users on a line is high, or if there are about the same number of users on a line at all times, a new multiplexing scheme should be used [3].

(b) Frequency division multiplexing (FDM): FDM is possible when the useful bandwidth of the transmission medium exceeds the required bandwidth of signals to be transmitted. In the frequency division multiplexing increases transmission capacity and flexibility by utilizing the very large bandwidth potential of the radio frequency.

In FDM, a number of frequency channels can be placed adjacent to each other to provide a large capacity of transmitted signals. Several messages can be simultaneously along the channel. To prevent interference, the channels are separated by guard bands, which are unused portion of the spectrum. TDM and FDM techniques are operated in the electrical domain and are widely used in the conventional radio wave communication. WDM techniques very useful in the optical domain and by WDM the bit rate can be increased beyond 10 Tb/s in the optical fiber communication.

(C)Wavelength division multiplexing (WDM): Since wavelength and frequency are closely related to each other, this form of multiplexing is often called frequency division multiplexing

(FDM). Each WDM fiber has a certain bandwidth - the range of frequencies it can carry. One advantage of WDM is that every user can transmit information at the highest rate possible all the time. WDM does not change 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. In any two fibers of the same quality, one signal will be lost just as fast as ten or more, so there is nothing to be lost—and much to be gained—from WDM. Even with the new solution to the bandwidth bottleneck, the ground gained by WDM was lost quickly, and another step forward had to be made [3].

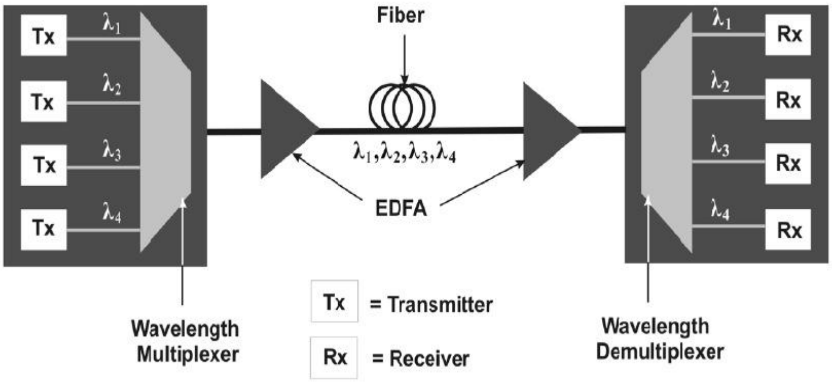


Fig.1.2 WDM [4]

1.4 Nonlinearities in optical fibers

Nonlinear effects in fiber may potentially have a significant impact on the performance of WDM optical communication systems. Nonlinearities in fiber may lead to attenuation, distortion, and cross-channel interference. In a WDM system, these effects place constraints on the spacing between adjacent wavelength channels, and they limit the maximum power per channel, the maximum bit rate, and the system reach [4].

1.5 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 (2.35* $10^{-20}m^2/w$ for silica). 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 designs.

1.6 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 channels; conversion to intensity «noise» by GVD.
Modulation instability (MI) (anomalous dispersion regime only) Selective amplification of noise.	**Four-wave mixing (FWM)** Generation of new spectral components; Crosstalk when overlap with other channels.
Stimulated Brillouin scattering (SBS) Retro diffusion of energy; Increases fibre loss.	Stimulated Raman scattering (SRS) Energy transfer from lower-wavelength channels to higher-wavelength ones.

1.6.1 Stimulated Raman Scattering

Stimulated Raman Scattering (SRS) is caused by the interaction of light with molecular vibrations. Light incident on the molecules creates scattered light at a longer wavelength than that of the incident light. A portion of the light traveling at each frequency in a Wan-active fiber is downshifted across a region of lower frequencies. The light generated at the lower frequencies is called the Stokes wave. The range of frequencies occupied by the Stokes wave is determined by the Raman gain spectrum which covers a range of around 40 THz below the frequency of the input light. In silica fiber, the Stokes wave has a maximum gain at a frequency of around 13.2 THz less than the input signal .The fraction of power transferred to the Stokes wave grows rapidly as the power of the input signal is increased. Under very high input power, SRS will cause almost all of the power in the input signal to be transferred to the Stokes wave. In multi wavelength systems, the shorter-wavelength channels will lose some power to each of the higher-wavelength channels within the Raman gain spectrum. To reduce the amount of loss, the power on each channel needs to be below a certain level. In a 10-channel system with 10-nm channel spacing, the power on each channel should be kept below **3** mW to minimize the effects of SRS [4].

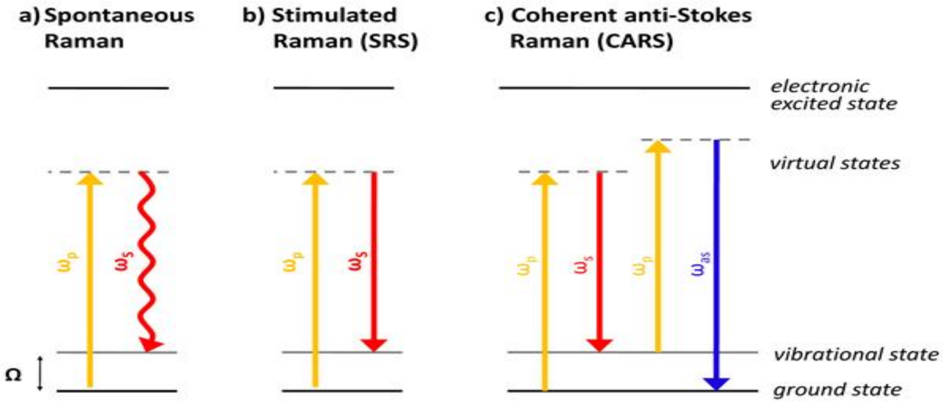


Fig.1.3: Energy diagrams of Raman interactions [4]

1) Effect and consequences

- SRS causes a signal wavelength to behave as a “pump” for longer wavelengths, either other signal channels or spontaneously scattered Raman-shifted light. The shorter wavelengths is attenuated by this process, which amplifies longer wavelengths
- SRS takes place in the transmission fiber

2) SRS could be exploited as an advantage by using suitable Raman Pumps it is possible to implement a Distributed Raman Amplifier into the transmission fiber. This helps the

amplification of the signal (in co-operation with the localized EDFA). The pumps are depleted and the power is transferred to the signal.

1.6.2 Stimulated Brillouin Scattering

Stimulated Brillouin scattering (SBS) is similar to SRS, except that the frequency shift is caused by sound waves rather than molecular vibrations. Other characteristics of SBS are that the Stokes wave propagates in the opposite direction of the input light, and SBS occurs at relatively low input powers for wide pulses (greater than 1ps), but has negligible effect for short pulses (less than 10 ns) . The intensity of the scattered light is much greater in SBS than in SRS, but the frequency range of SBS, on the order of 10GHz, is much lower than that of SRS. Also, the gain bandwidth of SBS is only on the order of 100MHz.To counter the effects of SBS, one must ensure that the input power is below a certain threshold [4]. Also, in multi wavelength systems, SBS may induce crosstalk between channels. Crosstalk will occur when two counter propagating channels differ in frequency by the Brillouin shift, which is around 11 GHz for wavelengths at 1550 nm. However, the narrow gain bandwidth of SBS makes SBS crosstalk fairly easy to avoid.

1.6.3 Four Wave Mixing

As the bit rate of optical data streams in fibers increases, four-wave mixing (FWM) is one principal among nonlinear effects in pulse propagation. FWM causes inter-channel crosstalk and is worst-case for equally-spaced WDM channels. FWM penalty can be mitigated by using fiber with high local dispersion (SMF, NZDSF) or unequally spaced channels. Even if using NZDSF can mitigate the FWM penalty, the minimum channel spacing has a lower limit. However, there are some significant motivations that are taking advantages of FWM in WDM networks. For example, FWM can be used to provide wavelength conversion [4**].** Four wave mixing (FWM) is common in DWDM systems where multiple wavelengths mix together to form new wavelengths, called interfering products. Interfering products that fall on the original signal wavelength become mixed with the signal, mudding the signal, and causing attenuation. Interfering products on either side of the original wavelength can be filtered out. FWM is most prevalent near the zero-dispersion wavelength and at close wavelength spacings.

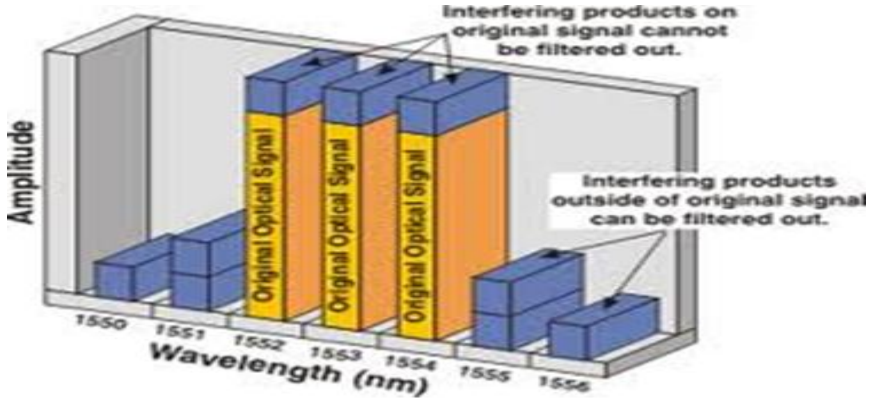


Fig.1.4: four wave mixing [5]

1.6.4 Self Phase Modulation

SFM is caused by variations in the power of an optical signal and results in variation in the phase of the signal. In phase shift-keying systems, SPM may lead to degradation of the system performance, since the receiver relies on the phase information. SPM also leads to spectral broadening of pulses. Instantaneous variation in a signal's phase caused by changes in the signal's intensity will result in instantaneous variation of frequency around the signal's central frequency. For very short pulses, the additional frequency component generated by SPM combined with the effects of material dispersion will also lead to the spreading or compression of the pulses in the time domain and affect the maximum bit rate and the bit error rate.

1.6.5 Cross Phase Modulation

Cross phase modulation (XPM) is a shift in the phase of a signal caused by the change in the intensity of a signal propagating at a different wavelength. XPM can lead to asymmetric spectral broadening, and combined with dispersion, may also affect the pulse shape in the time domain. XPM acts as a crosstalk penalty, which increases with increasing channel power level and system length and with decreasing channel spacing XPM causes a spectral broadening of the optical pulses and thus reduces the dispersion tolerance of the system at 10Gbps, its penalty is minimized by distributing dispersion compensation at each line amplifier site. If dispersion is compensated only at the terminal ends, there will be a residual penalty due to XPM

1.7 Objectives of the thesis

1) Comparison of four wave mixing effect for different values of ultra-low channel spacing
2) To investigate four wave mixing effect on bit error rate, Q-factor, eye opening and output spectrums as the channel spacing is increased.

3) To study the effect of chromatic dispersion on FWM, SPM and XPM in WDM systems.
4) Comparison of FWM effect on equal and unequal channel spacing in the presence of chromatic dispersion.
5) Compensation of chromatic dispersion and nonlilearities by using OPC.

1.8 Thesis Organization

The thesis is divided into nine chapters

Chapter 1 is dedicated to the overview of different types of nonlinearities in the WDM systems.

Chapter 2 includes the literature survey on the performance analysis of nonlinearities in the transmission system, the research done on the simultaneous effect of chromatic dispersion and nonlinearities and techniques for the compensation of both.

Chapter 3 outlines the effect of channel spacing and chromatic dispersion on FWM, the effect of chromatic dispersion on SPM and XPM. Overview of MSSI technique used for the compensation of nonlinearities using optical phase conjugator.

Chapter 4 gives the implementation of an 8- channel WDM system in which channel spacing is varied and results are compared to show the effect of FWM

Chapter 5 compares the effect of FWM by varying bit rate and modulator drivers in a 64-channel WDM system.

Chapter 6 shows the effect of chromatic dispersion on FWM.

Chapter 7 gives the design and implementation of a SPM limited system in the presence of chromatic dispersion.

Chapter 8 shows the design and implementation of XPM limited system in the presence of chromatic dispersion.

Chapter 9 presents the MSSI technique to compensate chromatic dispersion in the presence of nonlinearities using OPC.

Chapter 10 is dedicated to conclusion and future work

CHAPTER 2

LITRATURE SURVEY

Wavelength division multiplexing (WDM) can give two benefits at the same time: enhancement of transmission capacity and increase in flexibility in optical network design. It is possible to build long distance transparent optical transmission links without electrical regenerators with the help of erbium-doped fiber amplifiers (EDFAs). In such systems, fibre nonlinearities are likely to impose a transmission limit due to increased total interaction length. Most of the work so far has been concentrated on the study of the limitation of input power per channel imposed by fibre nonlinearities. There are a number of optical nonlinear effects in optical fibers, such as self phase modulation (SPM), cross phase modulation (XPM), Carrier Induced Phase Modulation and Four Wave Mixing (FWM). Out FWM is the dominant effect. The maximum possible transmission distance has been reported to be dependent on various system parameters like number of channels, channel spacing, the allowable power per channel, the amplifier spacing etc. Moreover Long haul communication system can be designed by wavelength division multiplexing of high-bit rate per channels. In such all-optical systems the effects of chromatic dispersion and nonlinearities accumulate during light propagation, imposing limits on the achievable performance .Chromatic dispersion, which broadens the pulses, can be reduced by using dispersion-shifted fibers (DSFs) at the 1550 nm wavelength range, but low chromatic dispersion enhances some nonlinear effects of fiber, especially four-wave mixing (FWM).

2.1 Research paper literature survey

Four wave mixing between the channels of a dense WDM system distorts the amplitude of a received data signal. As these amplitude distortions depend on the random optical phases and random data values in all channels of the WDM system, the MC method is used to compute the distribution of the eye closure. For a single span of nonzero dispersion fiber, this distribution function can be well approximated by a truncated two-sided exponential function. By convoluting this function, an analytical representation of the distribution after multiple amplified fiber spans is obtained. These functions were used to calculate the system degradation due to FWM. The parametric form of these functions enabled a simple formula, from which restrictions on the optical power, chromatic dispersion and channel spacing can be derived. It is found that the minimum channel spacing increases with the inverse square root of the chromatic dispersion such that CF permits an approximately three times closer channel packing density than NZDSF.

Yutaka Miyamoto et. al. [5] described recent technical challenges and the progress towards the realization of the optical transport network based on 43 Gbps channel. They proposed 43-Gbps per channel dense wavelength division multiplexing (DWDM) dispersion-managed transmission system using carrier-suppressed return-to-zero (CS-RZ) format.

Takehiro Tsuritaniet. al. [6] investigated ultra-long-haul 42.7-Gbps-based dense wavelength-division multiplexing (DWDM) transmission using optically prefiltered carrier-suppressed return-to-zero signal. They experimentally investigated the optimum filtering condition for 65 or 45 GHz wide prefiltered CS-RZ signals in the ultra-long-haul DWDM transmission and conducted the 70 and 50 GHz spaced 32 x 42.7 Gbps transmission using prefiltered CS-RZ signals.

Masahiro Daikokuet. al. [7] conducted single-polarization 160 Gbps-based field transmission experiments. They achieved single-channel transmission and 8 WDM transmissions with 300 GHz channel spacing over the inter-city 200 km SMF by utilizing 160 Gbps RZ-DPSK signals and a simple PMD compensator.

Lara D. Garrett et. al. **[8]** demonstrated a bidirectional transmission system with 16 10 Gbps dense wavelength division multiplexing channels on 32 wavelengths over 5000 km of nonzero dispersion-shifted fiber in a fully bidirectional recirculating loop, for a full-duplex capacity-distance product of 800 Tb/s/km.

G.Charletet. al. [9] evaluated the impact of available channel spacing on the Q-factor assuming RZ-DPSK format at 40 Gbps channel rate in five WDM experiments conducted in a recirculating loop over transoceanic distances. A degradation of the Q-factor by nearly 3 dB was observed when the channel spacing was reduced from 100 to 50 GHz.

Agarwal et. al. [10] 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.

David F.Geraghtyet. al. [11] 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.

S.J.B. Yooet. al. [12] reviewed various wavelength conversion techniques, discussed the advantages and shortcomings of each technique, and addressed their implications for transparent networks.

Yasin M. Karfaa et. al. [13] 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.

C.T. Politi et. al. [14] 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.

Hwang et. al. [15] described the comparisons of power penalty due to FWM between equal channel spacing and the unequal channel spacing for the20 channel WDM system. They show that for an intensity modulation/direct detection transmission system operating in an optical bandwidth of 16 nm with 0 dBm (1mW) peak optical input power per channel achieve BER ¼10-9 with an FWM cross-talk power of less than 1 dB, which was not achieved by a conventional equal channel spacing WDM system with 0.84 nm channel spacing.

Cartledge et al. [16] combined the use of SPM and joint optimization of the bias and modulation voltages to increase the dispersion limited transmission distance at 10 Gbps.

Tang et al. [17] presented a general treatment of multispan effects of Kerr nonlinearity on Shannon channel capacity for dispersion free nonlinear optical fiber transmission.

Chiang et al. [18] reported that the phase modulation induced by cross phase modulation is inversely proportional to the signal base band modulation frequency.

Yang et al. [19] derived expression for nonlinear crosstalk due to XPM effect.

Sono et al. [20] described WDM transmission with SPM/XPM suppression through pre chirping and dispersion management.

Yu et al. [21] demonstrated simultaneous demultiplexing and regeneration of 40 Gbps optical time division multiplexed (OTDM) signal based on self phase and cross phase modulation in dispersion shifted fibers.

The latest development of optical fiber communication technology in recent ten years has shown that the optical phase conjugation (OPC) technique can be successfully employed to overcome the limitations from chromatic dispersion and self- phase modulation respectively.

FISHER [22] showed the possibility of both dispersion and non-linearity compensation by the optical phase conjugation in lossless nonlinear and dispersive medium.

Chaloemphon and **Kazuro [23]** demonstrated the design theory of OPC for long distance transmission system.In this proposal a midway phase-conjugator is placed between two identical fiber systems and to generate a phase conjugate wave at frequency $\omega_{pc} = (\omega_0 - \Omega)$ with respect to the input signal wave of frequency $\omega_s = (\omega_0 + \Omega)$: It was theoretically proven that in this specific case, the chromatic dispersion and self-modulation influence from the first fiber system on the optical signal could be compensated by that from the second fiber system. In that original paper the midway phase-conjugator was suggested to be working with the method of backward non degenerate FWM under the following condition: $2\omega_0 = \omega_s + \omega_{pc} = (\omega_0 + \Omega) + (\omega_0 - \Omega)$; where ω_0 was the frequency of two counter-propagating pump beams.

Inoue [24] reinvestigated this issue theoretically and suggested the use of forward non degenerate FWM in an optical fiber as a new approach of midway phase conjugation [24]. To fulfil the phase-matching requirement of FWM, it was also suggested that ω_0; ω_s and ω_{pc} should be chosen working in the spectral region near to zero-dispersion wavelength.

Watanabe et al. **[25]** and **Jopson et al. [26]** reported the first demonstration of MSSI in a dispersion shifted fiber section using FWM.

Minizioni et al. [27] proposed optimized link design to exploit an optical phase conjugation for nonlinearity cancellation.

Watanable [28] proposed a new method to compensate exactly for both chromatic dispersion and self phase modulation in a transmission fiber, where the light intensity changes due to fiber loss and amplifier gain.

Xuefeng Tang and Zongyan Wu [29] gave the theoretical analysis and numerical simulations to reduce the intrachannel nonlinearities effect by using OPC combined with symmetric fiber link configuration.

2.2 Conclusion

The literature survey is done to investigate the performance of WDM systems in the presence of different types of nonlinearities. Study show that most of the degradation occurs due to optical Kerr effects. Most of the work so far has been done on the effects of FWM in WDM systems. The survey is also done on the research work to reduce the nonlinear effects by changing transmission parameters. It is found that some amount of chromatic dispersion reduces FWM up to some extent. However in most of the papers, nonlinearities are taken alone and the effect of chromatic dispersion and attenuation loss is not considered while investigating the limitations due to nonlinearities. In the proceeding chapters, the effect of FWM is evaluated at different channel spacing and by using different transmitter components. The work is further extended to investigate the effects of self phase modulation (SPM) and cross phase modulation (XPM). Also the designs of XPM, SPM and FWM limited systems in the presence chromatic dispersion have been presented. Finally a system is designed using OPCs to compensate both the effects.

CHAPTER 3

TRANSMISSION LIMITATIONS DUE TO NONLINEARITIES IN PRESENCE OF DIFFERENT PARAMETERS

Communication demands a rapid growth in its development due to its importance in each and every day activities. Optical communication, with its reliable transmission of data availability of high bandwidth, low power level requirements for input and minimal losses in the fiber channel proves to be a promising communication system over other forms of communication strategy. However the system is degraded by many nonlinear effects during the transmission. These nonlinear effects depends on various parameters in the transmission system.This chapter outlines the various parameters on which the nonlinearities depend as well as the combined effect of chromatic dispersion and nonlinearities. Here we have taken the three nonlinearities namely FWM, SPM and XPM. Four wave mixing is found to be highly dependent on the number of channels and the spacing between them. Apart from these nonlinearities, chromatic dispersion plays a major role in degrading the system performance especially in long haul communication systems. Thus one of the major transmission imparements is the signal distoration caused by the inperplay between fiber chromatic dispersion and nonlinearities.

3.1 Effect of four wave mixing on channel spacing

FWM is occurs when light of two or more different wavelengths is launched into fiber, giving rise to a new wave. It is a parametric process in which different frequencies interact and by frequency mixing generate new spectral component [30]. Fig.3.1 is a schematic diagram that shows four-wave mixing in the frequency domain. As can be seen, the light that was there from before launching, sandwiching the two pumping waves in the frequency domain, is called the probe light (or signal light). The idler frequency fiddler may then be determined by

$f\text{idler} = f\text{p}_1 + f\text{p}_2 - f\text{probe}$

where $f\text{p}_1$ and $f\text{p}_2$ are the pumping light frequencies, and $f\text{probe}$ is the frequency of the probe light [31, 32]. This condition is called the frequency phase-matching condition.When the frequencies of the two pumping waves are identical, the more specific term "degenerated four-wave mixing" (DFWM) is used, and the equation for this case may be written as $f\text{idler} = 2f\text{p} - f\text{probe}$; where: $f\text{p}$ is the frequency of the degenerated pumping wave.

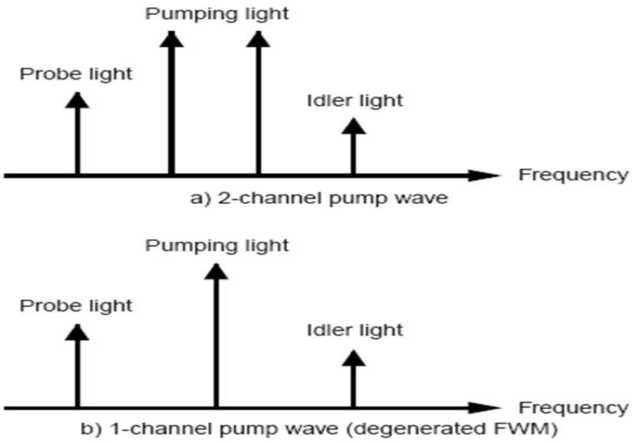


Fig.3.1. Schematic of four wave mixing in frequency domain [33]

In the transmission of dense wavelength-division multiplexed (DWDM) signals, FWM is to be avoided, but for certain applications, it provides an effective technological basis for fiber-optic devices. FWM also provides the basic technology for measuring the nonlinearity and chromatic dispersion of optical fibers. 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. In case of full in-line dispersion compensation, i.e., 100% dispersion compensation per span, the FWM crosstalk becomes of a maximum level since the FWM products add coherently in each span [34].

R.S kaler [35] compared the FWM effect at various values of channel spacing and revealed that 80GHz spacing has the edge over 6.25GHz spacing. It is found that spacing of 80GHz has the lowest BER and better system performance. Hence, higher spacing values between input channels is recommended for long distance transmission without four wave mixing.

Masahiro Daikoku et. al. [36] conducted single-polarization 160 Gbps based field transmission experiments. They achieved single-channel transmission and 8WDM transmission with 300 GHz channel spacing over the inter-city 200 km SMF by utilizing 160 Gbps RZ-DPSK signals and a simple PMD compensator.

Based on the literature survey following inferences can be made:

- FWM depends on channel spacing and number of channels. It decreases on increasing the spacing between the channels.
- FWM effect is maximum at ultra-low channel spacing.

- On comparing the limits of different number of channels, the power limit gets worse with an increasing number of channels. This effect is due to the larger number of FWM terms generated when number of channels is increased.
- Of the various methods adopted for reduction of FWM, optimization of channel spacing is the most effective one.
- Unequal channel spacing is found to be effective in reducing FWM than equal channel spacing.

3.1.1 Solutions for four wave mixing

The following actions can alleviate the penalty due to FWM:

1. Unequal channel spacing: the positions of channels can be chosen carefuly 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.
2. 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.
3. Reducing transmission power and amplifier spacing will decrease the penalty.
4. Using higher wavelengths with DSFs: a significant amount of chromatic dispersion is present in DSFs with high wavelengths which reduces FWM.

3.2 Chromatic dispersion in WDM systems

Chromatic dispersion results from the spectral width of the emitter. The spectral width determines the number of different wavelengths that are emitted from the LED or laser. Smaller the spectral width, fewer will be the number of wavelengths that are emitted. Because longer wavelengths travel faster than shorter wavelengths (higher frequencies) these longer wavelengths will arrive at the end of the fiber ahead of the shorter ones, spreading out the signal. Long haul communication system can be designed by wavelength division multiplexing of high-bit rate per channels. In such all-optical systems the effects of chromatic dispersion and nonlinearities accumulate during light propagation, imposing limits on the achievable performance. Chromatic dispersion, which broadens the pulses, can be reduced by using dispersion-shifted fibers (DSFs) at the 1550 nm wavelength range, but low chromatic dispersion enhances some nonlinear effects of fiber, especially four-wave mixing (FWM) [37,38].

Fig.3.2. Pulse broadening due to chromatic dispersion [37]

As mention earlier, chromatic dispersion alone is not the only degradation present in long haul communication systems. Other nonlinear effects also limit the system performance. The interplay between these nonlinearities and the chromatic dispersion causes a significant source of degradation. So the effect of dispersion with FWM, XPM and SPM have been studied and discussed as follows:

3.2.1 Effect of chromatic dispersion on FWM

In a WDM system using the angular frequencies $\omega_{1,....}\omega_n$, the nonlinear polarization causes three signals at frequencies ω_i, ω_j and ω_k to interact and produce signals at frequencies $\omega_i \pm\omega_j \pm \omega_k$ among these signals, the most troublesome one is the signal corresponding to $\omega_{ijk}= \omega_i +\omega_j - \omega_k$ depending on the individual frequencies this beat signal may lie on or very close to one of the individual channels in frequency resulting in significant crosstalk to that channel. In a multichannel system with ω channels, this effect results in a large number of interfering signals corresponding to I, j, k, varying from 1 to ω. In a system with three channels for example 12 interfering terms are produced as shown below:

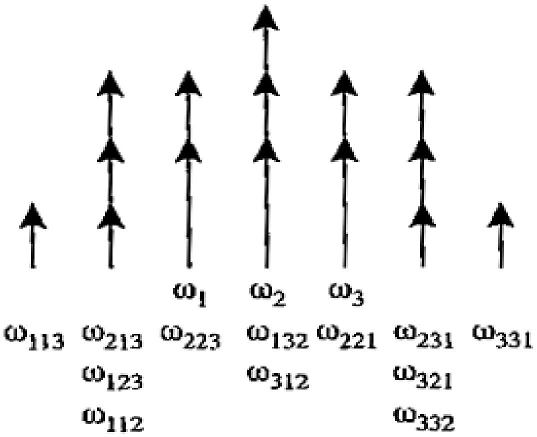


Fig. 3.3. WDM system with three channels

The effect of four wave mixing depend on the phase relationship between the interacting signals. If all the interfering signls travel with the same group velocity, as would be the case if there were no chromatic dispersion, the effect is reinforced. On the other hand with chromatic dispersion present, the different signals travel with different group velocities. Thus the different waves alternately overlap in and out of phase and net effect reduce the mixing efficiency. The velocity difference is greater when the channels are spaced farther apart (in system with chromatic dispersion)

3.2.2 Combined effect of SPM and chromatic dispersion

Long-haul high bitrate optical transmission systems are mainly limited in transmission distance by chromatic dispersion (CD), fibre attenuation and non-linear effects. With the fibre loss being compensated by erbium-doped fibre amplifiers (EDFA), CD and non-linearities become major factors that limit the bandwidth-length product.

The dominant non-linear effect in transmission systems such as time division multiplexing (TDM) and absolute polar duty cycle division multiplexing (AP-DCDM) is self-phase modulation (SPM), which arises because of the intensity-dependent component of the fibre refractive index. This non-linear refractive index causes an induced phase shift that is proportional to the intensity of the pulse. The different parts of the pulse undergo different phase shifts, which give rise to chirping of the pulses. Pulse chirping in turn enhances the pulse broadening effects caused by CD. This chirping effect is proportional to the launched power, which makes SPM effects to be more pronounced in the systems using high launched powers. Since high-speed and long-distance data transmission systems require large power for error-free detection, their performances are eventually limited by SPM effect.

3.2.3 Combined effect of XPM and chromatic dispersion

The nonlinear effect-XPM is caused by the modulation of the nonlinear refractive index by the total power in the fiber. The refractive index modulation due to one signal causes phase modulation in other co-directional channels. In the presence of chromatic dispersion, this would result in the modulation of the optical phase and the intensity of the various signals would be affected.

- Nonlinear refractive index seen by one wave depends on the intensity of other wave as:
  $\Delta n_{NL} = n_2 (|A_1|^2 + b\, |A_2|^2)$
  Total phase shift in fiber of length L_i: $\Phi_{NL} = (2\pi L/\lambda)\, n_2\, [I_1(t) + b\, I_2(t)]$
- An optical beam modifies not only its own phase but also of other co propagating beams.
- XPM induces nonlinear coupling and overlapping of optical pulses.

Chromatic dispersion is a result of the dependence of the refractive index on the wavelength. Different frequency components of the light wave experience different phase delays due to the refractive index change. The phase difference causes distortion on the signal. Waveguide dispersion results from the geometric properties of the fiber. Chromatic dispersion can lessen the effect of cross phase modulation.

Dispersion inhibits the effects of nonlinearities like self-phase modulation (SPM), cross-phase modulation (CPM) and four-wave mixing (FWM). Therefore, dispersion should be nonzero instantaneously; dispersion should be zero at the receiving end, in the long run. This puts the constraint into design of dispersion compensation techniques.

3.3 Compensation of chromatic dispersion and nonlinearities

Different techniques for compensation of chromatic dispersion are as follows:

- Fiber based method (using DFC): This employs dispersion compensation through a small section of fiber length. It consists of an optical fiber that has a special design such as providing a large negative dispersion coefficient while the dispersion of transport fiber is positive. Proper length of DCF allows the compensation of chromatic dispersion accumulated over a given length of transport fiber. Conventional DCF (DCF) has a high negative dispersion –70 to –90 ps/nm-km and can be used to compensate the positive dispersion of transmission fiber in C and L bands. Trough further reduction in the core effective area of new type DCF, some slope correction has been made possible for SMF [39].
- Fiber brag grating: The first FBG was demonstrated by Hill in 1978 [40]. A fiber brag grating is a type of distributed brag reflector is constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others. They are wavelength-selective mirrors written into the core of a single-mode fiber by UV light. The main drawback of dispersion compensating gratings is the group delay ripple caused by high-frequency deviation from the mean dispersion slope of the gratings over wavelength. Dispersion compensating modules (DCM) with FBG have narrow operating wavelength range and are not appropriate for broadband compensation within entire optical band [41].
- High-order-mode fibers (HOM): This is a new technique, which uses the fact that the high-order mode (LP02) has significant negative dispersion. The HOM based dispersion management devices are characterized by a nominal dispersion of –270 ps/nm-km at 1550 nm with a slope over the C-band approximately -5.6 ps/nm2 [39]. They can be used for dispersion and dispersion slope compensation in the whole optical band (C + L) for long haul DWDM transmission lines designed with NZ-DSF [42].

- Optical phase conjugator (OPC): It is possible, using nonlinear optical processes, to exactly reverse the propagation direction and phase variation of a beam of light. The reversed beam is called a conjugate beam, and thus the technique is known as optical phase conjugation.

The dispersion and nonlinearities both occur simultaneously in a system and play an important role in the degrading the overall performance of the optical communication system and networks. The interest in nonlinear fiber optics is expected to continue in view of the current emphasis on the development of photonics based technologies for information management.

The dispersion and nonlinear interactions of fiber material set an upper limit to the amount of information that can be transmitted. The significance of impairments becomes more critical while realizing ultrahigh dense wavelength division multiplexed systems (DWDM) that are used to exploit optical bandwidth. Particularly for long haul transmission with number of WDM channels, the accumulated nonlinear effects lead to waveform distortion and crosstalk between channels. Therefore, in order to realize broadband optical communication systems and networks, it is imperative to compensate the pulse spreading due to group velocity dispersion (GVD) and fiber nonlinearities due to optical Kerr's effects.

3.3.1 Mid way OPC for fiber communication systems

The latest development of optical fiber communication technology in the recent 10 years has shown that the optical phase conjugation (OPC) technique can be successfully employed to overcome the limitations from chromatic dispersion and self modulation (spectral self broadening) respectively. In this case a special optical phase conjugator is placed in the middle of two identical single-mode fiber transmission systems, which generates phase-conjugate waves of the input signal waves with an inverse spectral structure. This special technique adopted for fiber communications is called ''midway optical phase conjugation (MOPC)'' or ''mid-span spectral inversion (MSSI). The principle of this technique is based on the theoretical proposal reported by Yariv et al. in 1979 [43].

An optical communication system which uses optical phase conjugator to compensate for chromatic dispersion and optical Kerr effect includes a first fiber, a phase conjugator and a second fiber. The first fiber transmits a light signal therethrough. In a polarization maintaining fiber, the light signal is a linear polarized wave. The phase conjugator receives the light signal from the first fiber and produces a corresponding phase conjugated light signal. The second fiber receives the phase conjugated light signal from the first fiber and produces a corresponding phase conjugate light signal.

CHAPTER 4

INVESTIGATION OF SYSTEM PERFORMANCE AT ULTRA LOW CHANNEL SPACING IN THE PRESENCE OF FOUR WAVE MIXING

In this chapter, the four wave mixing effect has been compared 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. Here, all the channels are spaced evenly but at different values like 6.25 GHz, 10 GHz, 20 GHz, 25 GHz and 75 GHz. The simulation results reveal that four wave mixing is minimum at high wavelength spacings. 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.

4.1 Introduction

Four-wave mixing (FWM) (also called four-photon mixing) is one of the major limiting factors in WDM optical fiber communication systems that use the low dispersion fiber or narrow channel spacing. Normally, multiple optical channels passing through the same fiber interact with each other very weakly. However, these weak interactions in glass can become significant over long fiber-transmission distances. The most important is FWM in which three wavelengths interact to generate a fourth. FWM is due to changes in the refractive index with optical power called optical Kerr effect. FWM is a third- order non-linearity in silica fibers that is analogous to inter-modulation distortion in electrical systems. When three electro-magnetic waves with optical frequencies co-propagate through one fiber, they mix to produce a fourth inter-modulation product. In the FWM effect, three co- propagating waves produce nine new optical sideband waves at different frequencies. When this new frequency falls in the transmission window of the original frequencies, it causes severe cross talk between the channels propagating through an optical fiber. FWM occurs when light of three different wavelengths is launched into a fiber; it gives rise to a new wave. This newly generated wave as a result of FWM co-propagates with the originally transmitted signal and interferes with them. It causes severe degradation for the WDM channels and introduces the crosstalk and required power to reduce the crosstalk. When a high-power optical signal is launched into a fiber, the linearity of the optical response is lost. One such nonlinear effect, which is due to the third-order electric susceptibility, is called the optical Kerr effect. Four-wave mixing (FWM) is a type of optical Kerr effect, and occurs when light of two or more different wavelengths is launched into a fiber. The light present before launching, sandwiching the two pumping waves in the frequency domain, is called the probe light (or signal light). The idler frequency *f*idler may then be determined by

*f*idler = fp_1 + fp_2 – *f*probe where fp_1 and fp_2 are the pumping light frequencies, and *f*probe is the frequency of the probe light . This condition is called the frequency phase-matching condition. Multiwave mixing, especially four-wave mixing (FWM), is a fundamental process in nonlinear optics. Nonlinearity couples the underlying modes, generating new sum and difference frequencies from the original waves. In the typical scenario, two pump waves interact with a signal wave, creating a daughter wave that is phase conjugated with the signal. While dispersion creates issues of phase matching, FWM has proved useful in such applications as real time holography, super continuum generation, and soliton communication systems. The most common configuration involves a self-focusing nonlinearity and a backward geometry, in which the initial pump beams counter propagate to create a reflection grating. Comparison of power penalty for different fiber lengths and dispersion values has been done but the comparison on the basis of different spacing between input channels is rarely considered. In this chapter, comparison of four wave mixing is done for ultra-low values of spacing i.e. 6.25 GHz, 10 GHz, 20 GHz, 25 GHz, 75 GHz and their comparison has been done between different users.

4.2 Simulation setup

The simulation setup for showing the effect of changing spacing between the input channels on four wave mixing is shown in figure 4.1. The transmitter Tx_8 is a compound component having a continuous wave laser used to create the carrier signal. In this setup, eight users are taken in account whose wavelengths have a specific difference i.e. spacing between them. The frequency of first user is kept at 193.1 THz. The frequencies of next users are set as per the spacing requirement i.e. at wavelength difference of 6.25 GHz, 10 GHz, 20 GHz, 25 GHz, 75 GHz. The data source is used to generate the random input data bit sequence at the rate of 10 Gbps. The light signal modulates the input data. The modulator is driven by the modulator driver which decides the input data format. The input data format used here is NRZ raised cosine. The modulated data from all the users is combined using a combiner. The booster amplifies the signal before allowing it to enter into the fiber to avoid losses. Then this signal is sent over the fiber of length 50 Km. All the attenuation, dispersion and nonlinear effects are activated. The in-line amplifier (amplifies the signal in the transmission medium itself. At the receiver, the signal is demultiplexed by using a splitter which splits this signal into the same number of signals as were transmitted. The compound component Rx_8 is used where the photodiode is used for optical to electrical conversion. Then the signal is passed through the Bessel filter which is made to work as low pass filters and the final output signal is received. An electrical scope is kept at the receiver output to examine the eye diagram, BER, Q-factor. Some optical spectrum analysers and power meters are placed in the intermediate stages to analyse the input and the output.

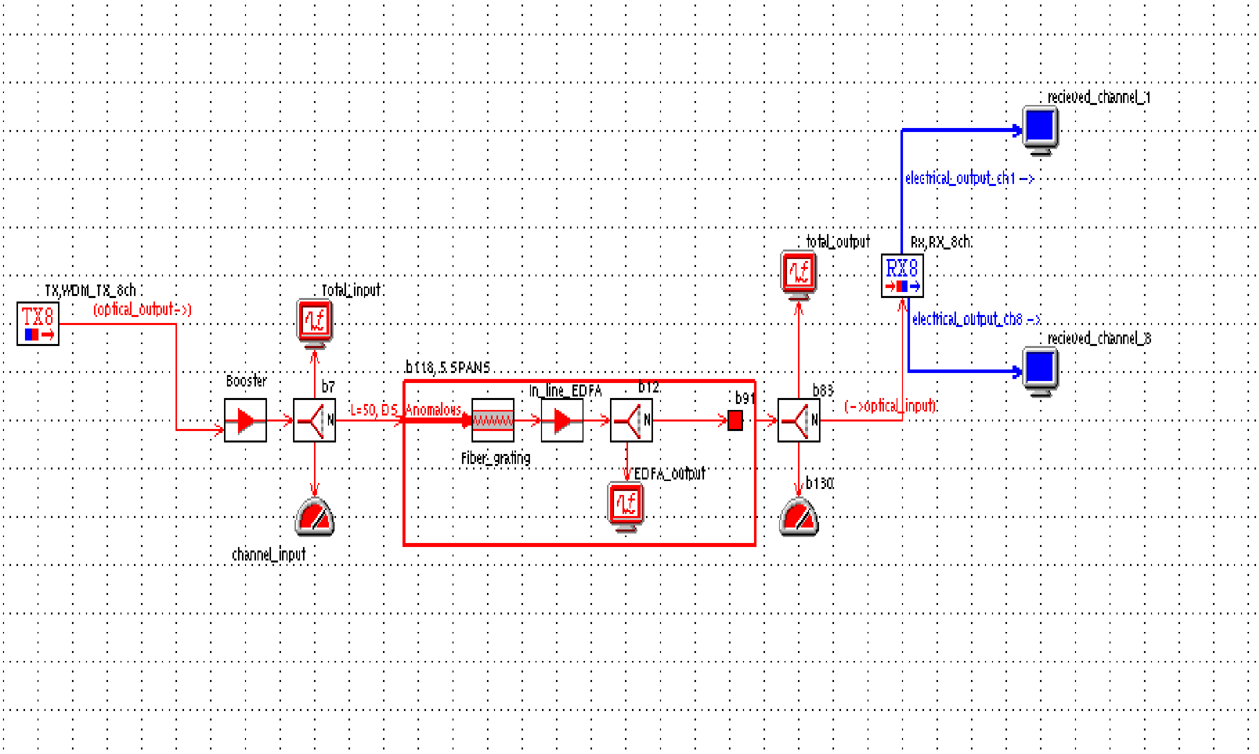


Fig.4.1. Simulation setup

4.3. Results and discussion

Using simulation setup, the value of BER, Q-factor, eye diagrams, input and output optical spectrums are measured. Optical scope measures the input and output wavelength spectrums. BER, eye diagrams and Q-factor is measured at the receiver output by using an electrical scope. Figure 4.2 shows the input optical spectrum for the spacing of 20 GHz between input channels.

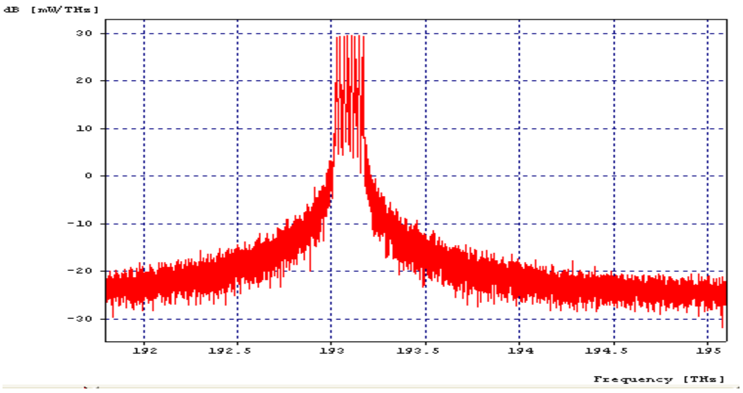


Fig.4.2. Input spectrum for the spacing of 20GHz

On changing the spacing between the different users, the peaks get shifted to the frequencies as specified in the laser. There are eight input channels so eight peaks appear in the input spectrum.

Figure 4.3 represents the output spectrum for the various values of spacing between the input users. Figure 4.3 (a) shows the output spectrum for the spacing of 6.25 GHz. Figure 4.3 (b) shows the output spectrum for the spacing of 10 GHz. Figure 4.3 (c) shows the output spectrum for the spacing of 20 GHz. Figure 4.3 (d) shows the output spectrum for the spacing of 25 GHz. Figure 4.3(e) shows the output spectrum for the spacing of 75 GHz.

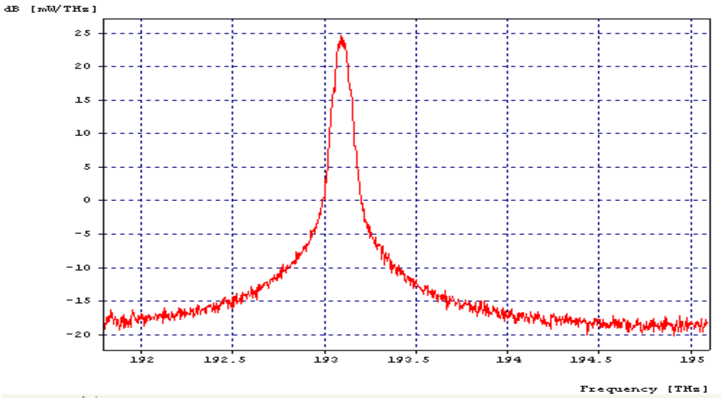


Fig.4.3(a). Output spectrum for 6.25 GHz spacing

In the input spectrum, the peaks of various frequencies were occurring at the sides of input spectrum. As the channels come closer, the peak frequencies of each channel get very closer to one another which cause the output peak to be high. The four wave mixing effect is clearly seen in the above output spectrum for 6.25 GHz spacing. Moreover the peaks at the input frequencies have also diminished due to four wave mixing occurred after crossing the nonlinear fiber.

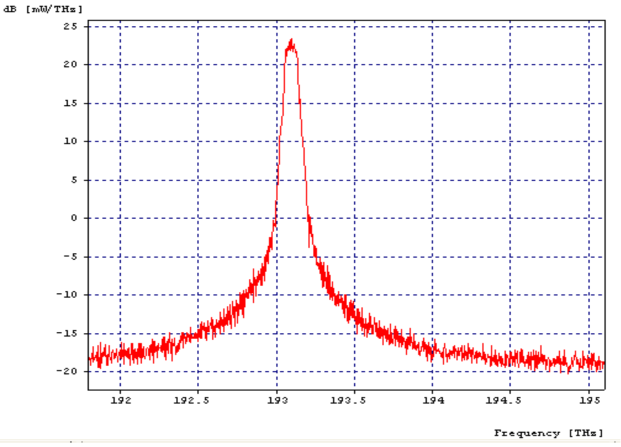


Fig.4.3(b). Output spectrum for 10 GHz spacing

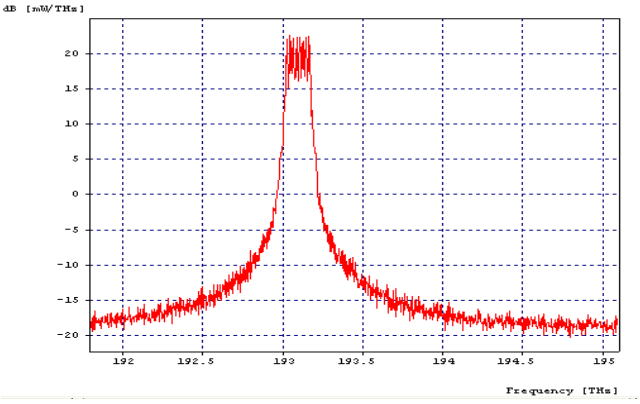


Fig.4.3(c). Output spectrum for 20 GHz spacing

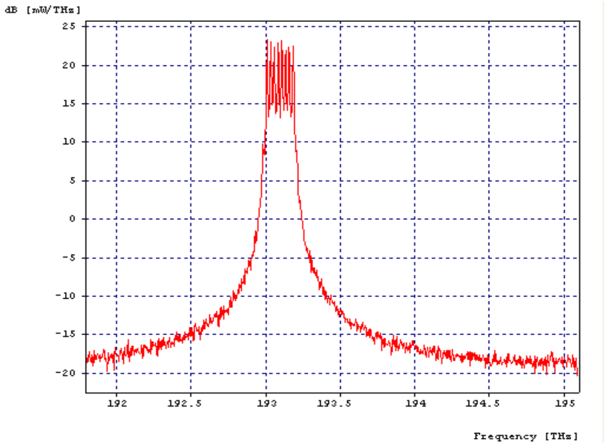


Fig.4.3(d). Output spectrum for 25 GHz spacing

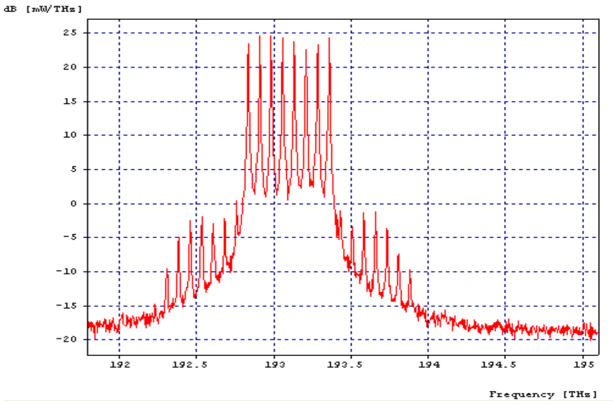


Fig.4.3(e). Output spectrum for 75 GHz spacing

The above spectrums shows that as the spacing between the input channels/users increases, the four wave mixing effect goes on decreasing. The unwanted peaks are maximum when the spacing is 6.25 GHz and are minimum when the spacing is 75 GHz. This shows that lesser the spacing between different input users/channels, more is the interference between the input frequencies i.e. more is the four wave mixing effect. On increasing the spacing between the input channels, the four wave mixing decreases.

Figure 4.4 shows the variation of BER on the basis of spacing between the input channels. The figure shows that BER goes on decreasing with the increasing spacing. BER of a system is defined as the number of errors occurring over a certain period of time by total number of pulses transmitted during this interval and given by: BER= N_{error}/N_{total}.

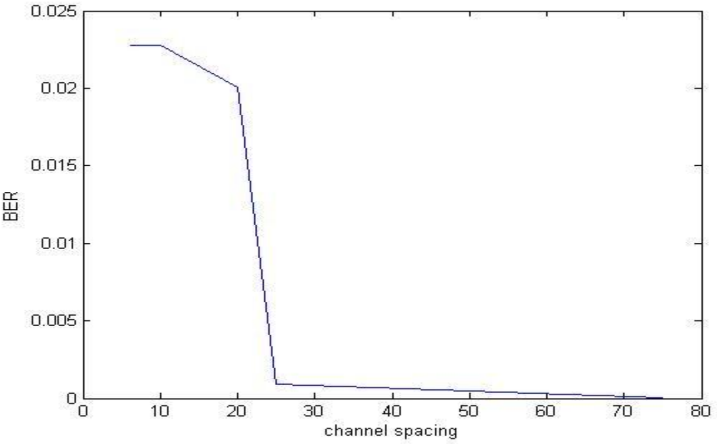


Fig.4.4. Variation of BER with respect to channel spacing

As we know the relation between BER and Q-factor is given by: BER= $(1/2\pi)(e^{-Q^{\wedge}2/2}/Q)$

If Q-factor of a system or design increases, then BER decreases (BER and Q-factor are inversely proportional)

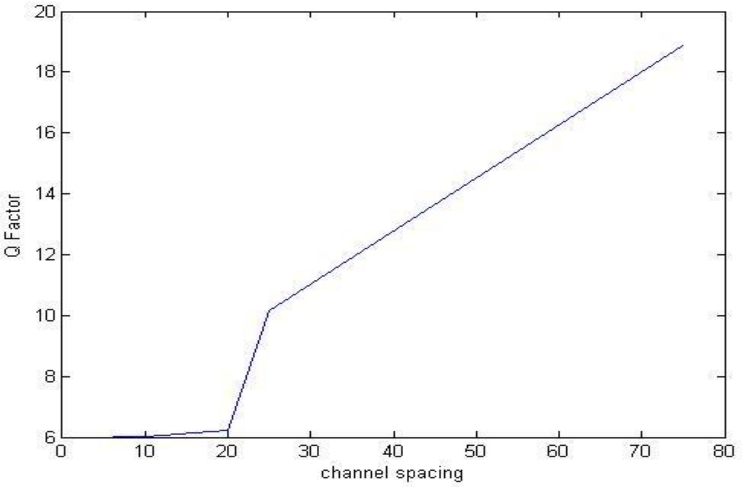


Fig.4.5. Variation of Q-factor with respect to channel spacing

Figure 4.5 shows the variation of Q-factor with the spacing between the input channels. The graph shows that the Q-factor increases on increasing the channel spacing. It is maximum when the channel spacing is 75 GHz and is minimum when the channel spacing is 6.25 GHz.

Figure 4.6 shows the eye diagrams for the various values of channel spacing. Figure 4.6 (a) shows the eye diagram for 6.25 GHz spacing. Figure 4.6 (b) shows the eye diagram for 10 GHz spacing. Figure 4.6 (c) shows the eye diagram for 20 GHz spacing. Figure 4.6 (d) shows the eye diagram for 75 GHz spacing.

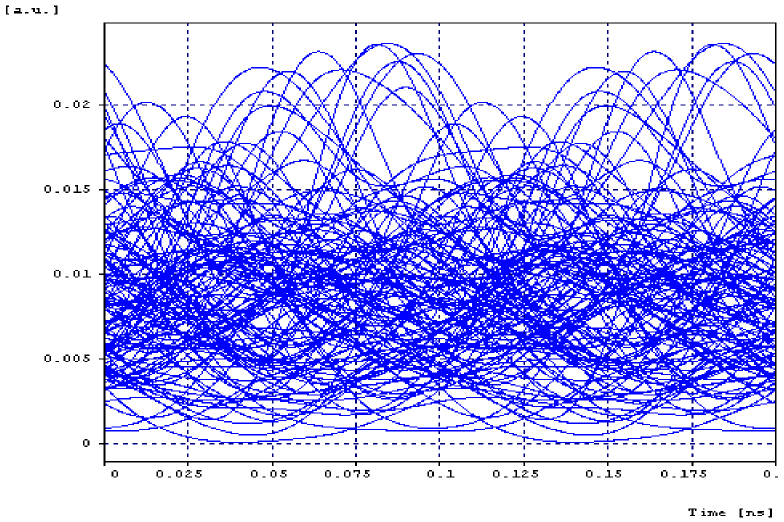


Fig.4.6(a). Eye diagram for 6.25 GHz spacing

The above eye diagram shows that there is large interference between the input frequencies. The BER is quite large at 6.25 GHz. Thus, four wave mixing is quite large when the spacing between the input channels is 6.25 GHz.

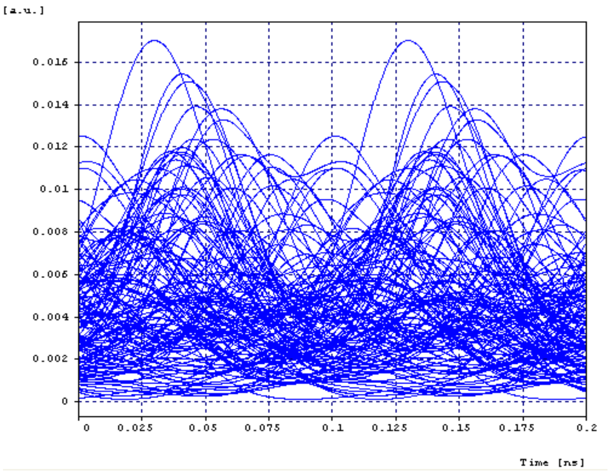


Fig.4.6(b) Eye diagram for 10 GHz spacing

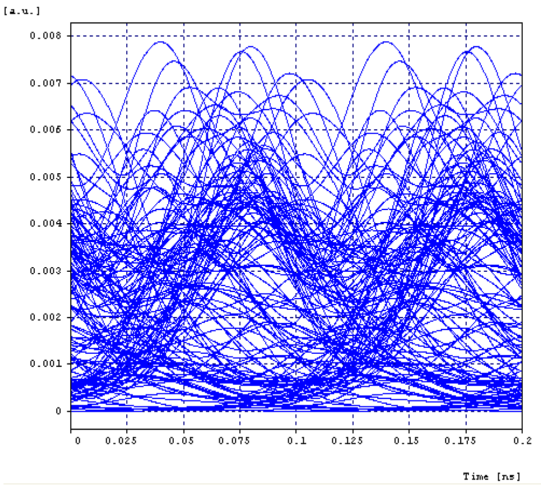


Fig.4.6(c) Eye diagram for 20 GHz spacing

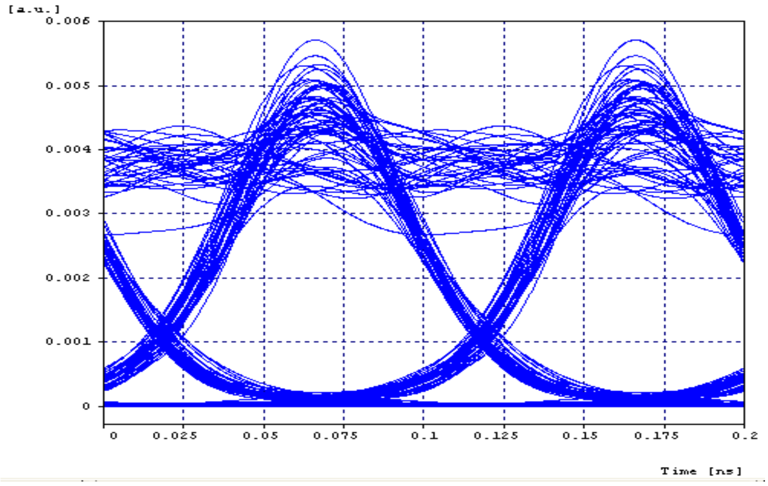


Fig. 4.6(d) Eye diagram for 75 GHz spacing

The above eye diagrams show that the eye diagram clarity goes on increasing with the increasing spacing between the input channels. This shows that the interference between the input frequencies and hence the four wave mixing effect decreases with the increasing channel spacing.

4.4. Conclusion

In this chapter, the design, implementation and performance analysis of four wave mixing in optical communication system for different values of spacing between input channels is presented. The comparison of four wave mixing effect at various values of channel spacing revealed that 75 GHz spacing has the edge over 6.25 GHz spacing in optical communication system. It is found that spacing of 75 GHz has the lowest BER and better system performance. Hence, the higher spacing values between the input channels are recommended for long distance transmission without four wave mixing. It can be seen from the graphs of BER, Q-factor and eye opening that higher channel spacing gives the best performance as compared to lower channel spacing. Hence, it is concluded that higher channel spacing is best suitable to be employed in the optical communication systems minimizing the four wave mixing effect.

CHAPTER 5

PERFORMANCE ANALYSIS OF FOUR WAVE MIXING EFFECT WITH DIFFERENT OPTICAL TRANSMITTER COMPONENTS

This chapter contains the design, implementation and performance analysis of four wave mixing in optical WDM system on changing the different transmitter components and the extent of four wave mixing is shown for each component separately. Components involve different data sources like pn-sequence generator with different bit rate (10 Gbps and 20 Gbps), modulator drivers like RZ raised cosine, NRZ and RZ rectangular, RZ super Gaussian, RZ soliton; After that, four wave mixing effect has been compared for all components in terms of output spectrums, and eye opening. The simulation results revealed that for wave mixing effect remains same on changing the bit rate of the data source. Four wave mixing is minimum when RZ rectangular modulator driver is used.

5.1 Introduction

The FWM power generated at the end of fiber due to interaction of channels at frequencies, f_i , f_j and f_k is given by

$P_{FWM} = ((1024\ \pi_6)/(n4\ \lambda_2\ c^2))[D\chi]^2((P_i\ P_j\ P_k)/A_{eff}))L_{eff2}\ \eta\ e^{-\alpha L}$

Where P_i, P_j and P_k refer to the soliton input power at frequency fi, fj and f_k respectively, n is the fiber effective refractive index, λ is the zero dispersion wavelength, c is the velocity of light, χ is the 3rd order nonlinear susceptibility of the single mode fiber, A_{eff} is the effective mode area of the fiber, L_{eff} is the fiber effective length, a is fiber attenuation coefficient and D is the degeneracy factor, where D = 6 for i = j and D = 3 for $i \neq j$.

The FWM light generation efficiency is given by

$$\eta = (\alpha^2/(M^2\ (\alpha^2\ + \Delta\beta^2)))\ ((\sin^2\ (M\ \Delta\beta\ L_{a/2}))/(\sin\ (\Delta\beta\ L_{a/2})))$$
$$.\ (1 + (4\ \exp(-\alpha L_a)\ \sin^2(\Delta\beta\ L_{a/2}))/(1 - \exp(-\alpha L_a))^2$$

where M refers to the number of fiber sections and $\Delta\beta$, the phase mismatching constant, in general, can be written as $\Delta\beta = \beta\ (f_i)+\beta\ (f_j)-\beta\ (f_k)-\beta\ (f_{FWM})$ where β represents the propagation constant [44].

Up till now, various methods to reduce four wave mixing effect have been proposed and theoretically compared but the comparison on the basis of different components is rarely considered. In this chapter, four wave mixing effect is compared on changing the different components like data sources; modulators as linear amplitude, linear electro absorption, phase modulator; modulator drivers like NRZ and RZ raised cosine, NRZ and RZ rectangular, RZ super Gaussian, RZ soliton.

5.2. Simulation setup and description

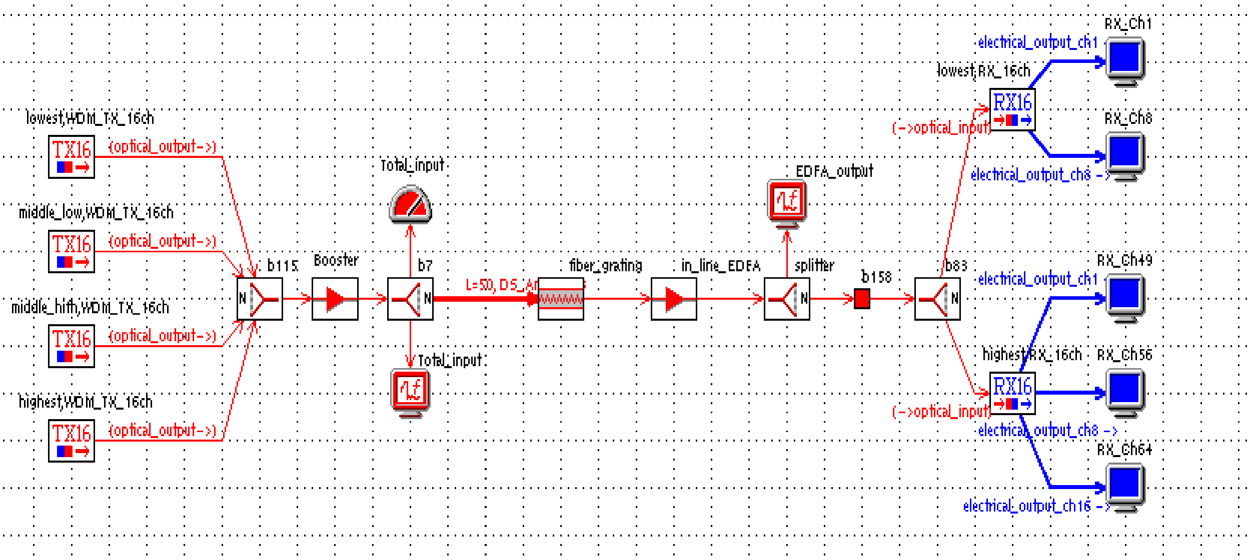


Fig.5.1. simulation set up

A. <u>Transmitter section</u>

The simulation setup shown above shows the implementation of a 64 channel WDM system. The transmitter section consists of four blocks compound component having transmitters of 16 channels each. Hence a total of 64 channels are combined together in a combiner and the combined signal is boosted by a booster and sent to the fiber.

B. <u>Fiber section</u>

The fiber used here is a DS anomalous of length 50 Km. Fiber grating is used for the compensation of dispersion.an inline EDFA is used for pre amplification .All the attenuation, dispersion and nonlinear effects are activated. The in-line amplifies the signal in the transmission medium itself

The signal is demultiplexed using a splitter and is received at the receiver.

C. Receiver section

The receiver section is having two blocks of compound component, each of 16 channel receiver. Each block is having a photo diode, which converts the optical signal into electrical and a Bessel filter to filter the output. Each of the receiver blocks is provided with two electrical scopes to view the output signal.

5.3. Results and discussion

5.3.1. Effect of changing the bit rate of data source

Figure 5.2 shows the output spectrum for the different bit rates of data source.

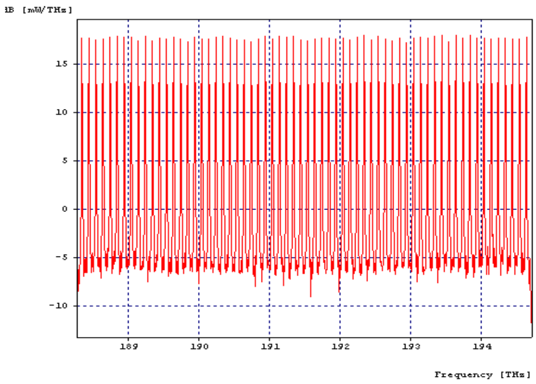


Fig 5.2(a) Bit rate 10Gbps

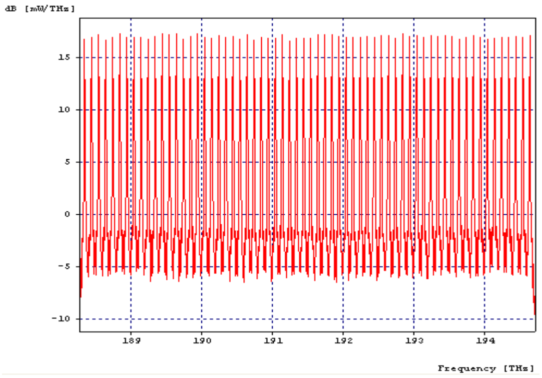


Fig 5.2(b) Bit rate 20Gbps

The above spectrums show the effect of different bit rates of the data source on the four wave mixing at the output. There is no effect of changing the bit rate of the data source on the output spectrums. Thus we can say that FWM remains unaffected on changing the bit rate of the data source.

5.3.2. Effect of changing modulator drivers

Figure 5.3 shows the effect of changing modulator drivers on the four wave mixing at the output. Different modulators whose effects are studied are: NRZ rectangular, RZ rectangular, RZ raised cosine, RZ super Gaussian and RZ soliton.

Fig.5.3(a) and 5.3(b) shows the output spectrum and eye diagram for NRZ rectangular modulator driver.

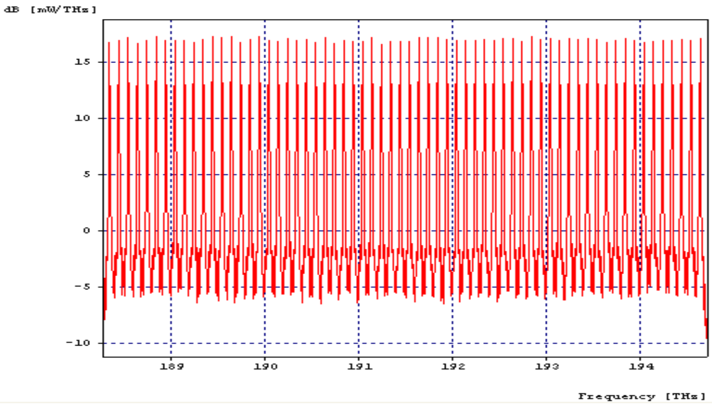


Fig.5.3(a). Output spectrum for NRZ rectangular

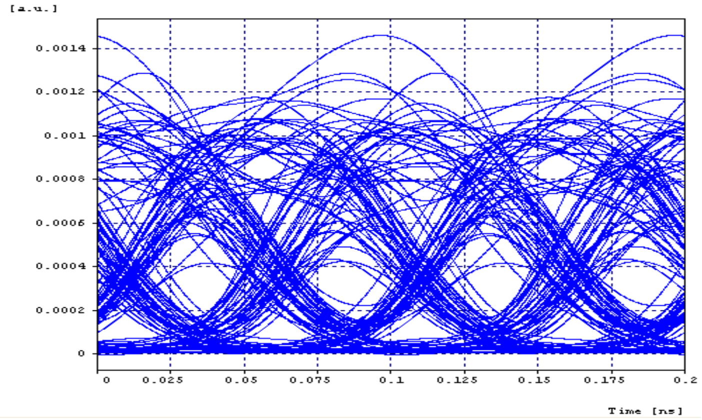


Fig.5.3(b). Eye diagram for NRZ rectangular

Fig.5.4(a) and 5.4(b) shows the signal spectrum and eye diagram for RZ rectangular modulator driver. Similarly Fig.5.5 is for RZ raised cosine modulator and Fig.5.6 and 5.7 for RZ super Gaussian and RZ soliton respectively.

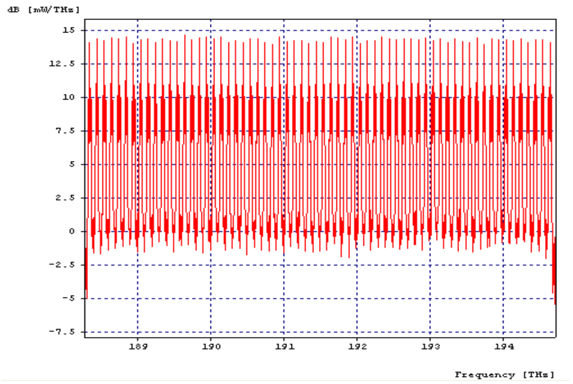


Fig.5.4(a) Spectrum for RZ rectangular

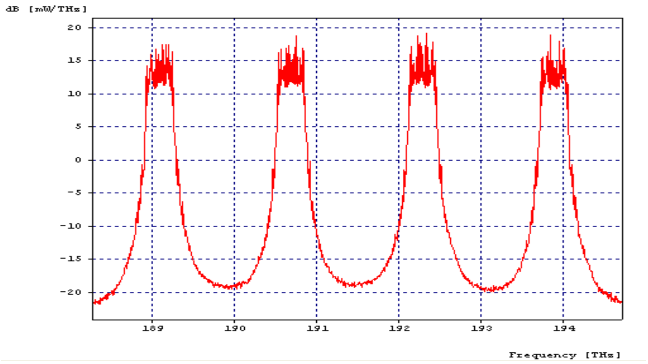


Fig.5.5(a) Spectrum for RZ raised cosine

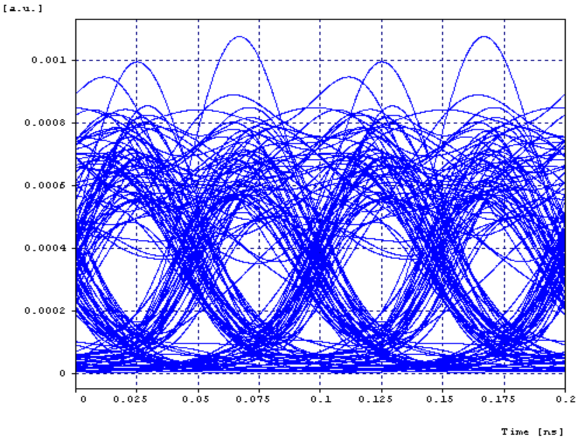


Fig.5.4(b) Eye diagram for RZ rectangular

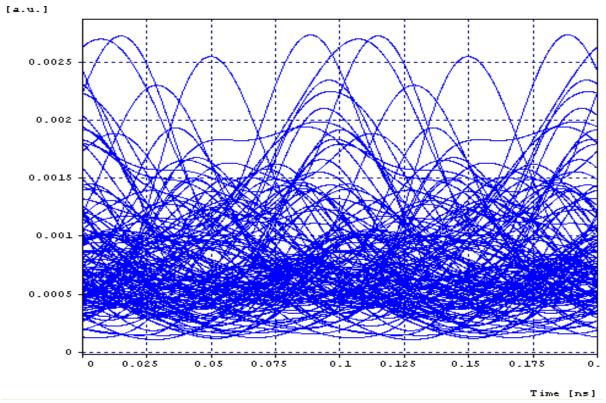
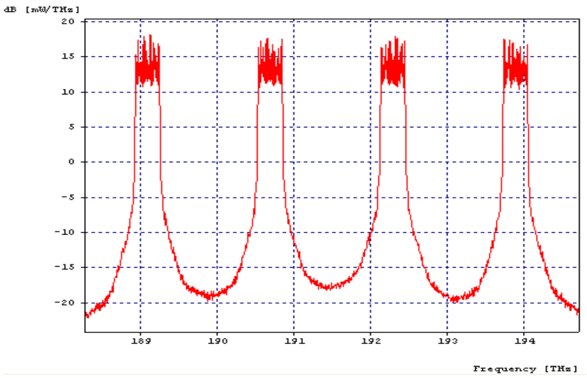


Fig.5.5(b) Eye diagram for RZ raised cosine



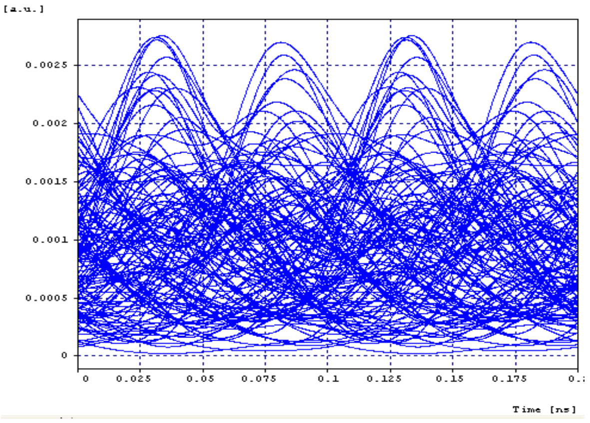


Fig.5.6(a) Spectrum for RZ super Gaussian

fig.5.6 (b) Eye diagram for RZ super Gaussian

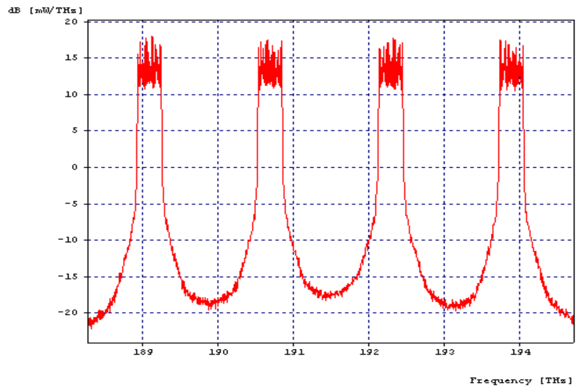


Fig.5.7(a) Spectrum for RZ soliton

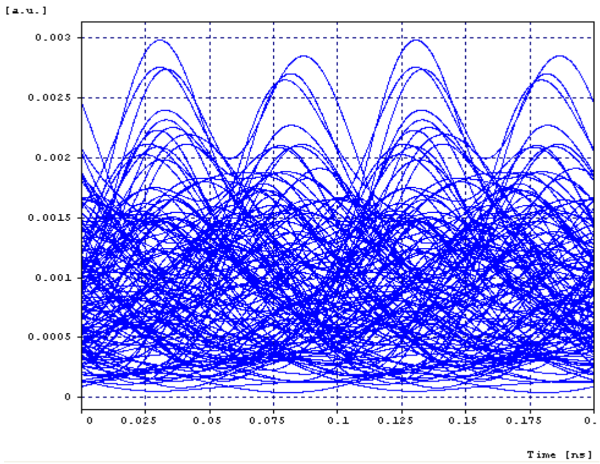


Fig.5.7(b) Eye diagram for RZ soliton

From the above diagrams, it is clear that signal spectrums vary on changing the modulator drivers; they affect the amount of FWM. It is inferred that RZ rectangular driver gives the output much clear than the others. So to reduce FWM, RZ rectangular modulator can be used.

5.4 Conclusion

In this chapter, the design and implementation of 64 channel WDM system has been done. The performance analysis of four wave mixing in optical communication system for different bit rates and modulator drivers is presented. The comparison of FWM with different bit rates revealed that changing the bit rate of the data source does not affect the four wave mixing at the output. Changing the modulator drivers however has an effect on FWM. It is found that as compared to the various modulators, RZ rectangular modulator driver gives a better performance and can be used in the systems where FWM has to be minimum.

CHAPTER 6

EFFECT OF CHROMATIC DISPERSION ON FWM IN OPTICAL WDM TRANSMISSION SYSTEM

Crosstalk due to four-wave mixing (FWM) is the dominant nonlinear effect in long haul multi-channel optical communication system which can severely limit system performance. In this chapter, the effect of chromatic dispersion on FWM using equal and unequal channel spacing in terms of input/output spectrum and eye diagram is simulated. Results show that the effect of FWM reduces with the increasing dispersion coefficient, but the reduction is more effective for unequal channel spacing than equal channel spacing.

6.1 Introduction

Very high capacity, Long haul communication system can be designed by wavelength division multiplexing of high-bit rate per channels. In such all-optical systems the effects of chromatic dispersion and nonlinearities accumulate during light propagation, imposing limits on the achievable performance [45]. Chromatic dispersion, which broadens the pulses, can be reduced by using dispersion-shifted fibers (DSFs) at the 1550 nm wavelength range, but low chromatic dispersion enhances some nonlinear effects of fiber, especially four-wave mixing (FWM) [46-47]. FWM is of particular concern on account of its relatively low threshold power and rises very quickly as the number of channels increased. The number of FWM product with channel number is shown in Fig.1. The efficiency of FWM crosstalk generation can be reduced by increasing the frequency separation between the various channels, increased channel separation would preclude dense WDM systems [48]. To suppress FWM-induced crosstalk in WDM systems in DSF, the unequal channel-spacing scheme was proposed and worked quite well for most cases since it avoids generating FWM products to fall on to any channels [49-50]. However, the newly produced FWM products can mix with channel signals or themselves to produce higher-order FWM products which can overlap with channels and result in crosstalk. In this chapter, we have simulated the effect of FWM products in an intensity-modulated direct-detection WDM environment by varying the chromatic dispersion parameter for equal and unequal channel spacing. It is observed that the effect of FWM is maximum channel the chromatic dispersion coefficient is zero.

6.2 Theoretical analysis

Chromatic dispersion depends on the phase relation between the interacting signals. If all the interfering signals travel with the same group velocity as would be the case if there were no chromatic dispersion, the effect is reinforced. On the other hand with chromatic dispersion present, the different signals travel with different group velocities. Thus the different waves alternately overlap in and out of the phase and the net effect is to reduce the maximum efficiency. The velocity difference is greater when the channels are spared farther apart(in systems with chromatic dispersion). To quantify the power penalty due to four wave mixing, we can start from the following equation:

$P_{ijk}= (w_{ijk}\ n\ d_{ijk}/ 3cA_e)^2\ P_iP_jP_k\ L^2$

This equation assumes a link of length L without any loss and chromatic dispersion. Here $P_{i,}$ P_j and P_k denote the powers of the mixing waves and P_{ijk}, the power of the resulting new degeneracy factor. In the real systems both FWM and chromatic dispersion are present, to take the loss into account, L is replaced with effective length L_e, which is given by the following equation for a system of length L with amplitude spacing l Km apart

$L_e= 1- e^{-\alpha l}/\alpha\ L/l$

The presence of chromatic dispersion reduces the efficiency of mixing. This can be modulated by assuming a parameter η_{ijk}, which represents the efficiency of mixing of three waves at frequencies ω_i, ω_j and ω_k. taking these into account, we can modify the preceding equation to

$P_{ijk}= \eta_{ijk}\ (\omega_{ij}\ n\ d_{ijk}/3cA_e)\ P_iP_jP_kL_e^2$

The efficiency, $\eta_{ijk}= \alpha^2/\alpha^2+ (\Delta\beta)^2\ [1+4e^{-\alpha l}\sin^2(\Delta\beta l/2)/(1-e^{-\alpha l})^2$

Here $\Delta\beta$ is the difference in the propagation constants between different waves and D is the chromatic dispersion. The efficiency has a component that varies periodically with the length as the interfering waves go in and out of the phase for the maximum value of this component, the phase mismatch can be calculated as

$\Delta\beta= \beta_i + \beta_j - \beta_k- \beta_{ijk}$

FWM manifests itself as intra channel crosstalk. The total crosstalk power for a given channel ω_c is given as:

$\Sigma\omega_i + \omega_j - \omega_k = \omega_c\ P_{ijk}$

6.3 Simulation setup and description

In this work, optsim simulator is used that gives the environment almost the exact physical realisation of a fiber-optic transmission system. Optsim provides the users with laser diodes, filters, modulators and all the components which are essential to build an optical network. The simulation setup for a pump-probe configuration for NRZ modulator is shown in the Fig.6.1. The simulation is carried out to observe the effect of FWM in WDM configuration in the presence of chromatic dispersion at 10 Gbps.

A. Transmitter section

The transmitter consists of data source which generates pseudo random bit sequence at the rate of 10 Gbps. The bit sequence is fed to NRZ coder that produces an electrical NRZ coded signal. This signal is modulated using $\sin^2$ modulator. The modulator is driven by a CW_Lorentzian laser. Three channels are used in this simulation.

B. Fiber section

The combined optical signal is fed into the fiber which is a single mode fiber. The fiber model in OptSim takes into account the unidirectional signal flow, stimulated and spontaneous Raman scattering, Kerr nonlinearity and dispersion. Here, we can set the length, dispersion parameters, attenuation, nonlinear index, core area of the fiber and FWM options. At the output of the fiber, the probe signal would have undergone the FWM effects and the waveforms at the output become distorted. Fiber dispersion is completely compensated at each span through ideal fiber gratings. A parametric run on fiber dispersion is performed to show dependency of FWM effect on dispersion value.

C. Receiver section

At the output of the trapezoidal optical filter (for the probe channel), a photodiode converts the optical signal into an electrical signal. An electrical low pass Bessel filter follows the avalanche photodiode. This has a cut-off frequency determined by the type of the waveform used for modulation and is 193.175 THz. Finally at the output of the low pass filter, Optsim provides a visualization tool called Scope. It is an optical or electrical oscilloscope with numerous data processing options, eye display and BER estimation features. If the eye opening is very wide and there is no crosstalk. Eye diagrams can be used to effectively analyse the performance of an optical system so that it can be easily visualized

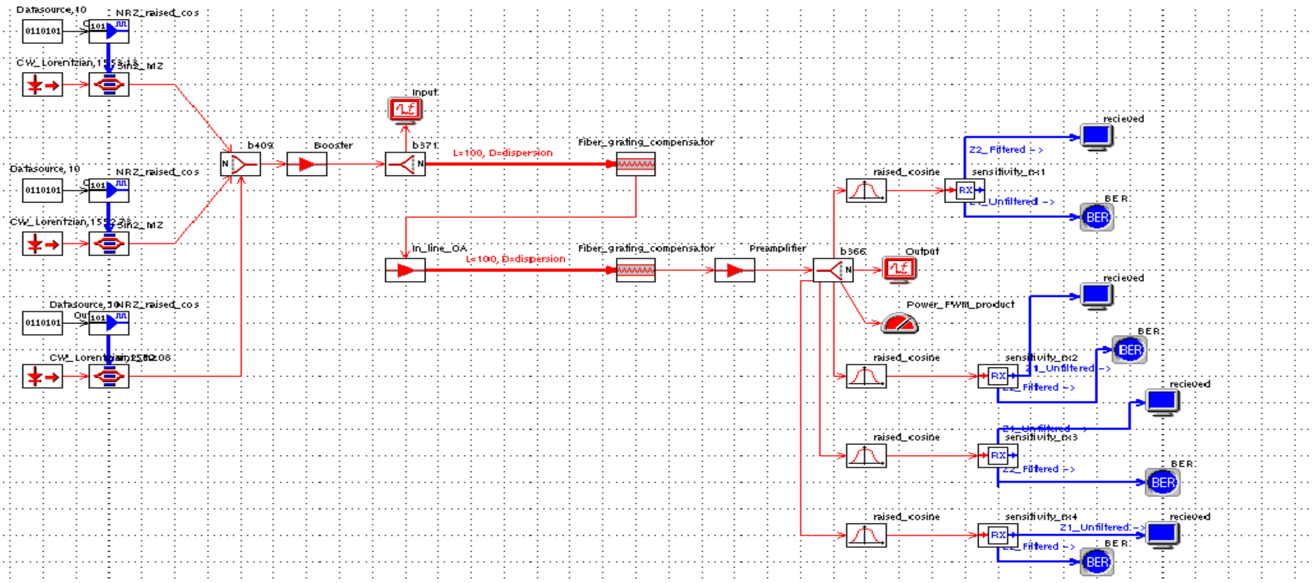


Fig.6.1. Simulation set up diagram of a 3-channel WDM system

6.4 Results and discussion

The simulation setup described above have investigated the effect of FWM on WDM optical transmission system in terms of eye diagrams, input/ output spectrums, input pump power and probe power etc.

The channels are modulated at 10 Gbps data rate using NRZ format. The distance between the in-line optical EDFA fiber amplifiers is 100 Km (span length). The fiber dispersion value is varied from 0-4ps/nm-Km through parametric runs. The three signals are launched at 193.025 THz, 193.1 THz and 193.175 THz respectively, so that they have 75 GHz uniform spacing.

Table.6.1 shows the simulation parameters used in the setup and their values

PARAMETER (Unit)	VALUES
Pump frequency (THz)	193.025- 193.175
Probe frequency (THz)	193.1
Channel separation (GHz)	50
Bit Rate (Gbps)	10
Attenuation(dB/Km)	0.2
Fiber length(Km)	100
Dispersion coefficient (ps/nm-Km)	0-4
Booster amplifier gain(dBm)	6
Preamplifier gain	25

Table.6.1. Simulation parameters

. The optical spectrum for input signal is shown in Fig.6.2. The output spectrum of the signals for D= 0 ps/nm-km and D=4 ps/nm-km are shown in Fig.6.3 and Fig.6.4 respectively. The output signal spectrums show that with the increase of dispersion the peak of the FWM effect in the spectrum is suppressed decreases. At zero dispersion co-efficient the effect becomes significant and it generates other wavelengths of significant amplitude which are taking power from its parent signal. On the other hand, at Fig.6.4 at dispersion co-efficient of 4ps/nm-km generated other wavelengths amplitude significantly small.

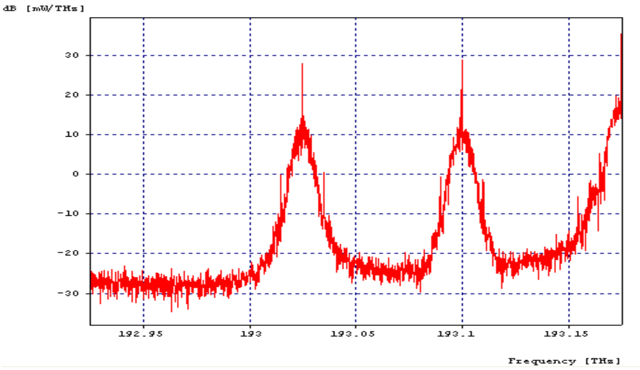


Fig.6.2. Input spectrum of 3-channels with equal channel spacing

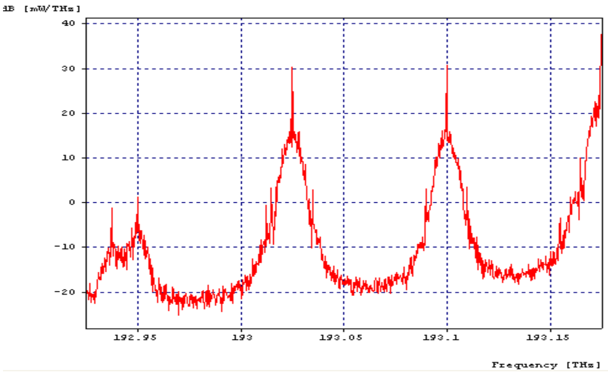


Fig.6.3. Output spectrum of 3-channel with equal channel spacing (when dispersion coefficient, D=0)

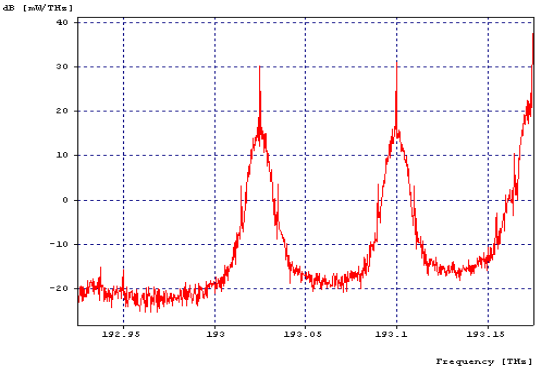


Fig.6.4. Output spectrum of 3-channels with equal channel spacing (when dispersion coefficient, D=4

The performance of the probe channel (which is 193.1 THz) is also monitored at the receiver end by observing the eye diagram formation for equal as well as unequal channel spacing by varying the dispersion parameter. Fig.6.5 and Fig.6.6 shows the effect of zero dispersion for equal and unequal channel spacing respectively. It is found that the link performance of unequal channel spacing is better than equal channel spacing.

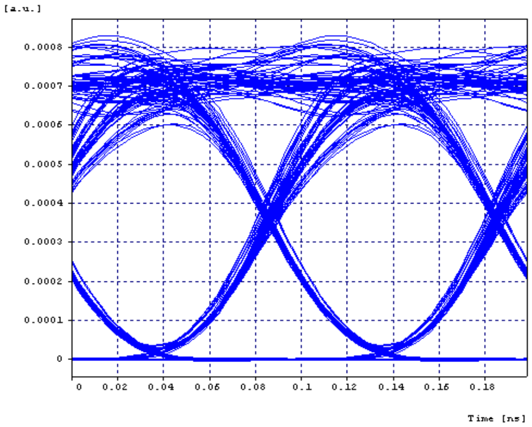


Fig.6.5. Eye diagram for equal channel spacing (when dispersion coefficient, D=0)

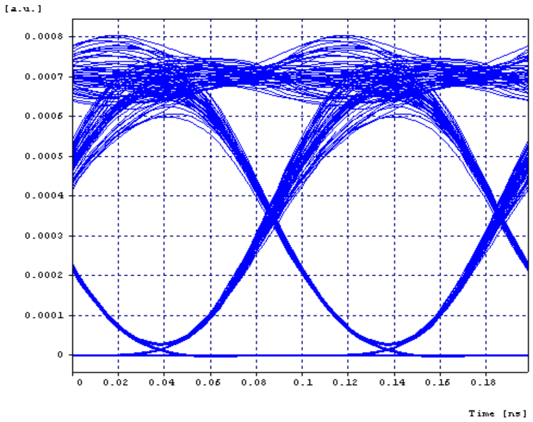


Fig.6.6. Eye diagram for unequal channel spacing (when dispersion coefficient, D=0)

In the above eye diagrams, the four wave mixing effect in case of unequal channel spacing has been slightly reduced and thus we can say that the performance of a WDM system is better with unequal channel spacing. However the reduction is more significant even with equal channel spacing when dispersion coefficient is increased. This is shown in fig.6.7.

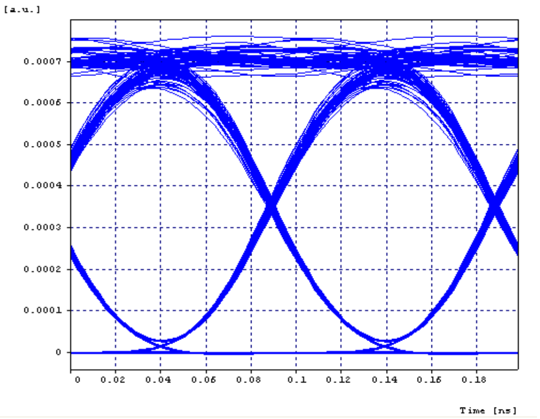


Fig.6.7. Eye diagram for equal channel spacing (when dispersion coefficient, D=4)

6.5. Conclusion

The impact of dispersion coefficient on FWM in a 3-channel WDM system has been demonstrated in this paper. The effect has been shown for both equal and unequal channel spacing. Results show that FWM is maximum when dispersion coefficient is minimum and reduces as the dispersion coefficient is increased. Also the performance of the system is found to be better with unequal channel spacing. Therefore in a WDM system in order to improve performance, unequal channel spacing is recommended with an optimized level of chromatic dispersion.

CHAPTER 7

SELF PHASE MODULATION EFFECT ALONG WITH DISPERSION IN A 10Gbps WDM SYSTEM

This chapter presents a self modulation limited transmission system with data rate 10 Gbps, in the presence of chromatic dispersion. The design and implementation of the system has been presented. The effect of chromatic dispersion is taken into account by giving different values of chromatic dispersion at each simulation run. The self phase modulation effect is shown to be dependent upon the dispersion coefficient and tends to reduce at a certain value of chromatic dispersion. It is shown that although the simultaneous effect of these two limits the system performance; however by adding some amount of chromatic dispersion, the effect of self phase modulation can be reduced to some extent.

7.1 Introduction

Self-phase modulation (SPM) is a nonlinear optical effect of light-matter interaction. An ultra-short pulse of light, when travelling in a medium, will induce a varying refractive index of the medium due to the optical Kerr effect. This variation in refractive index will produce a phase shift in the pulse, leading to a change of the pulse's frequency spectrum. Self phase modulation is an important effect in optical systems that use short, intense pulses of light, such as lasers and optical fibre communications systems.

The combined effect of SPM and dispersion causes two interesting phenomenon with may consequence for the real tramsmission systems:

- Modulation instability
- Solitons

7.2 Simulation setup and description

A 10 Gbps NRZ signal is sent over four fiber spans of 100Km each. Dispersion is completely compensated to isolate the SPM phenomenon. Dispersion values have been varied from -10 to10 ps/nm-Km through the parametric run feature. The power at the fiber input for each span has been set to 10 dBm. EDFA noise has been turned off. By decreasing the dispersion modulus, SPM grows and depletes the signal. In passing from the normal to the anamolous dispersion regime, the received optical spectrum at first widens and then narrows.

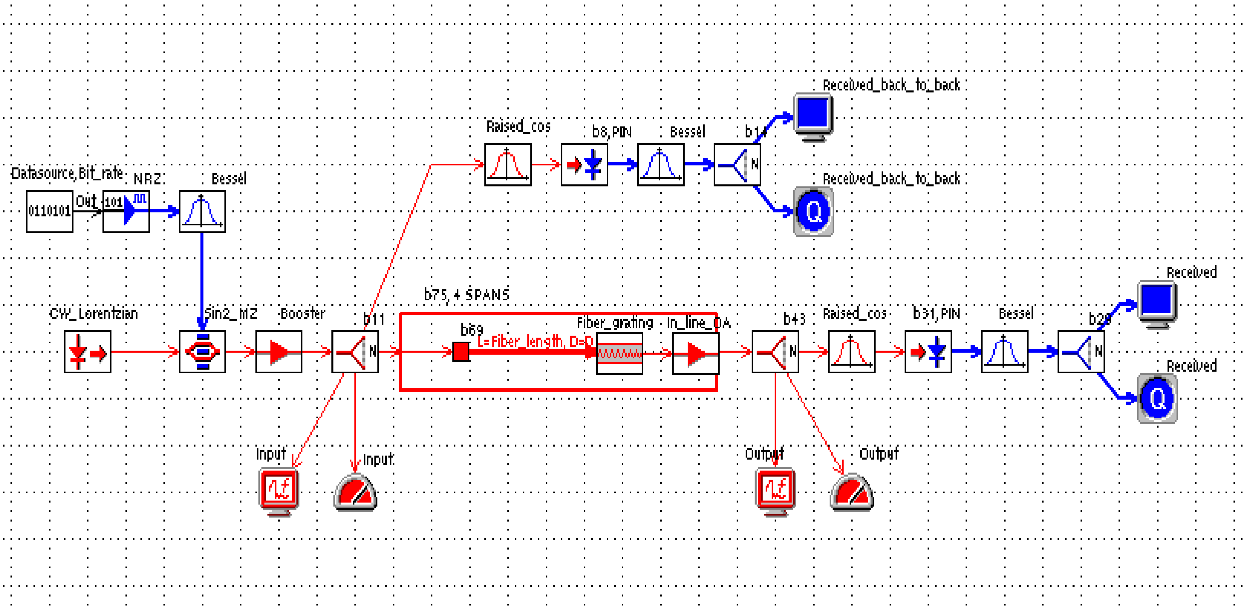


Fig.7.1. Simulation Setup

A. <u>Transmitter section</u>:

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

B. Fiber section:

Fiber channel in the design is shown as iterative loop component. The iterative loop component consists of fiber, fiber compensating technique component and In-line optical amplifier. The iterative loop is used to resend the signal within the block depending on iteration number. Iteration number is set in the iterative block properties. Use of an iterative loop makes the design more reliable and aids in the observe of the quality of output signal by increasing the fiber length. The input optical signal is send over the fiber. The fiber has few important parameters, which needs to be considered and configured. They are Length of the fiber, losses, dispersion coefficient, nonlinear effects and nonlinear coefficient. Output of the fiber is sent to fiber grating, which is used to compensate the distortion of signal by inducing dispersion after each stage. Fibers grating compensator is used to reflect particular wavelengths of light and transmits others, achieved by varying refractive index (varying intensity of light). Dispersed signal is then sent to an Inline optical amplifier to amplify signal. Inline optical amplifiers are used for simple amplification because effect of dispersion is small when we use single mode link fiber.

C. Receiver section:

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

7.3 Results and discussion

Table.7.1 shows the simulation parameters used in the setup and their values.

PARAMETER	VALUE
Transmission rate	10 Gbps
Amplitude of input	-2.5 to 2.5
Power of light wave	-4 mW
Length of fiber	100 Km
Wavelength	193.4 THz

Table.7.1. Simulation parameters and their values

Fig.7.2 and Fig.7.3 shows the input signal waveform and its eye diagram respectively. The input signal's waveform shown here is the output of the Bessel filter and is visualized as almost a sinusoidal waveform (not and instantaneous switching between the levels). The output of filter and CW laser are sent to amplitude modulator, which generates an optical signal at the output of modulator. It can be clearly seen from the eye diagram that there is no distortion in the input signal.

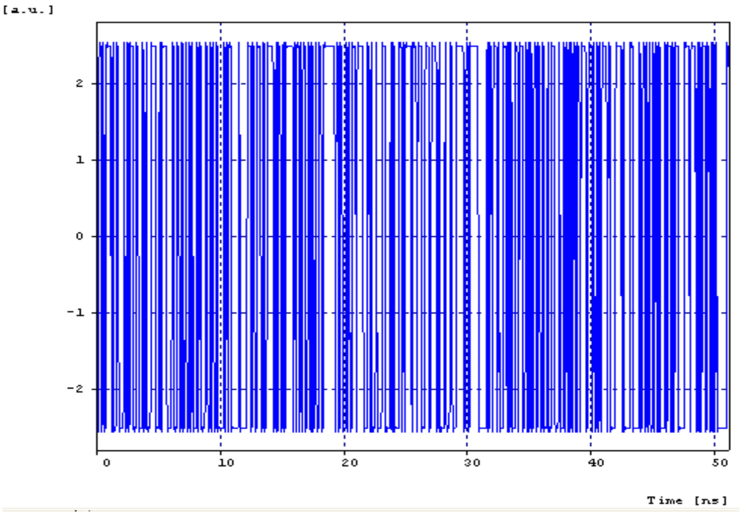


Fig.7.2. sinusoidal input waveforms

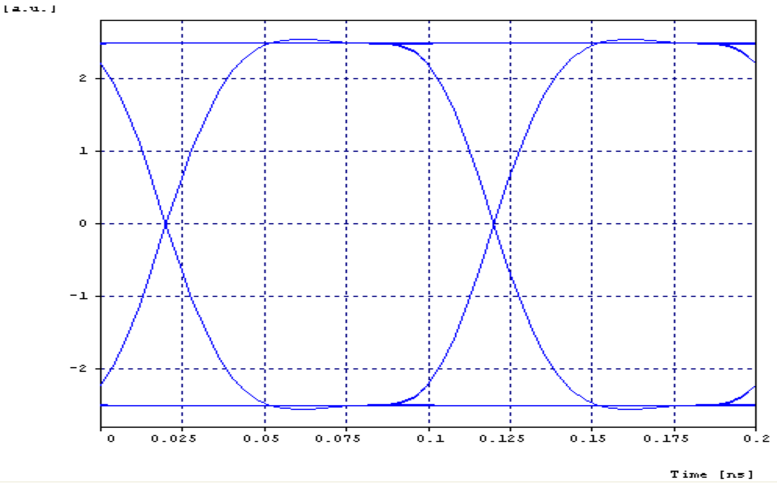


Fig.7.3. Input eye diagram

Fig.7.4 shows the input optical signal transmitted to the fiber channel. This signal is the output of the booster which is before the fiber. The signal is amplified with the factor 10. The output signal from the fiber channel is sent to the receiver block. Fig.7.5 shows the output of the fiber which is again amplified by the booster. The difference between the two spectrums shows the amount of dispersion caused by the fiber.

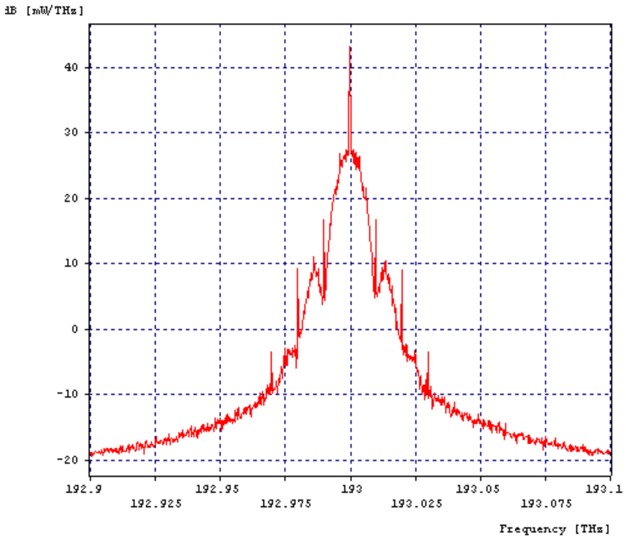


Fig7.4. Input signal after the booster block

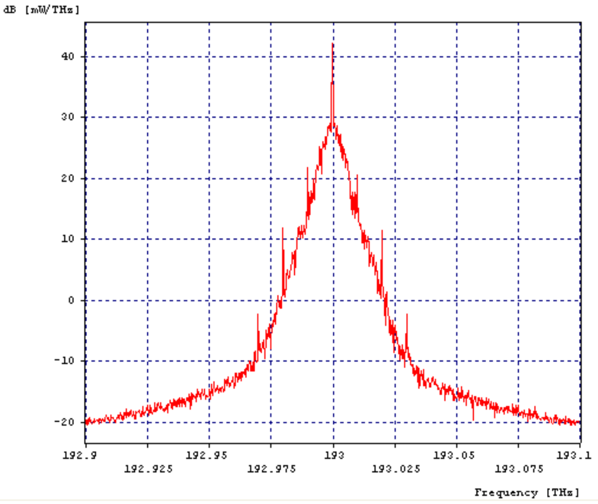


Fig.7.5. Output from the fiber after the booster block

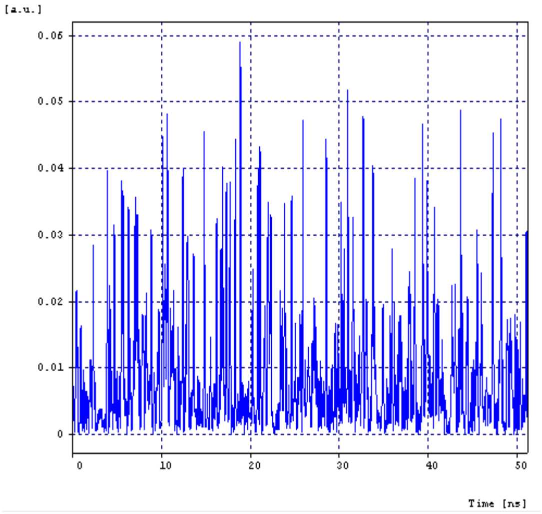


Fig.7.6. Received signal spectrum (D= -10 ps/nm-Km)

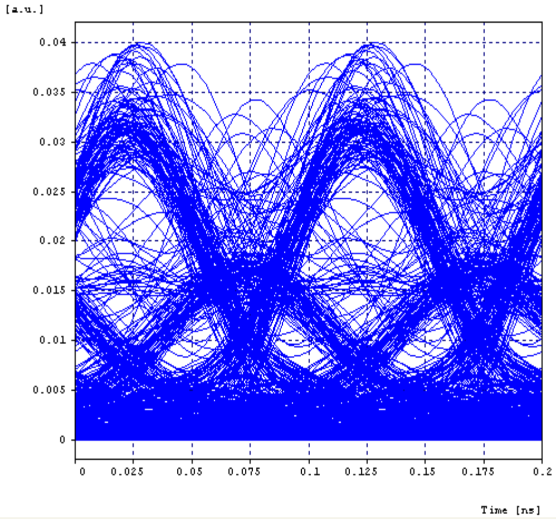


Fig.7.7. Received output waveform(D= -10 ps/nm-Km)

Fig.7.6 and 7.7 shows the output waveform and the eye diagram respectively of the received signal at the output of receiver. As mentioned in the simulation setup, the dispersion coefficient is varied from -10 to10 ps/nm-Km by varying the simulation runs from 1 to 6. Fig.7.7 shows the eye diagram at D= -10 ps/nm-Km. Fig.7.8 to 7.12 shows the eye diagrams of the received signal at various dispersion coefficients.

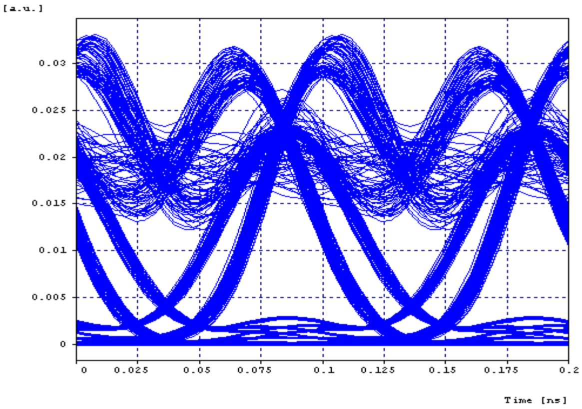


Fig.7.8. Received signal (D= -5 ps/nm-Km)

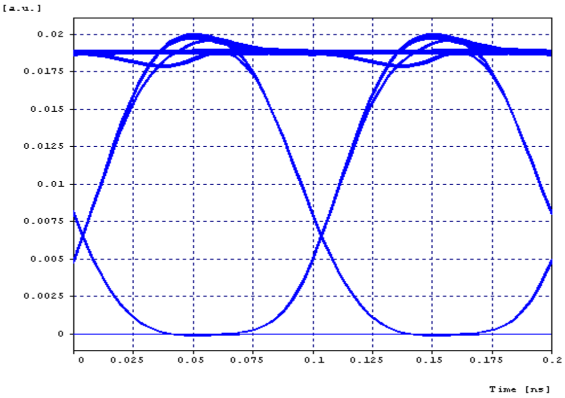


Fig.7.9. Received signal (D= -2 ps/nm-Km)

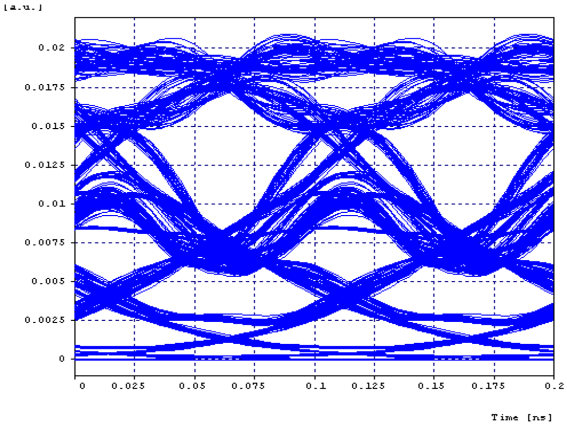


Fig.7.10. Received signal (D=2 ps/nm-Km)

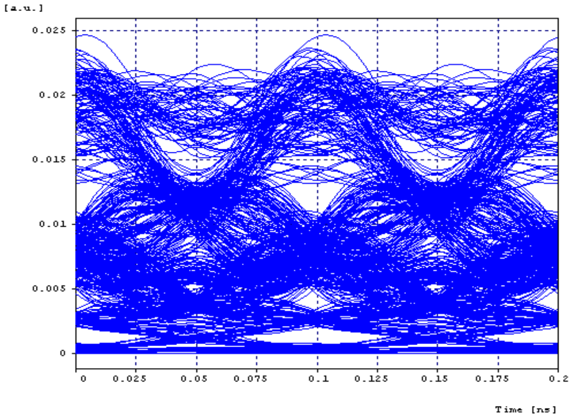


Fig.7.11. Received signal (D=5 ps/nm-Km)

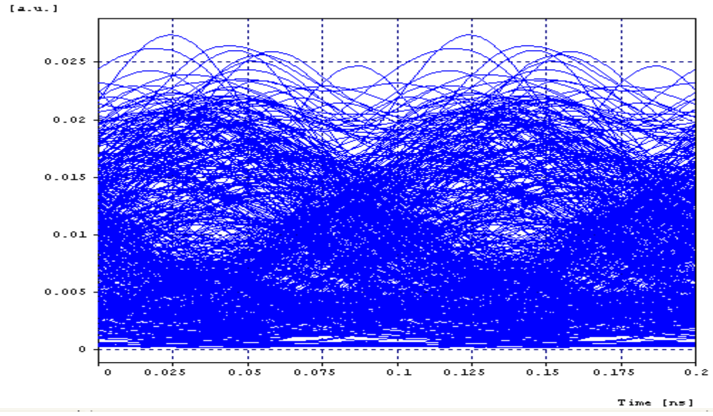


Fig.7.12. Received signal (D=10 ps/nm-Km)

It is seen in the eye diagrams that as we go on increasing the dispersion coefficient, there is some improvement in the eye. The eye is completely open at D=-2 ps/nm-Km without any nonlinear effect. This means that on increasing the dispersion value upto some extent, SPM decreases. But as the dispersion coefficient is further increased, self phase modulation is increased causing the closing of the eye. SPM is maximum at D= 10 ps/nm-Km.

Fig.7.12 and 7.13 shows the graphs of input and output power respectively. The graphs are ploted between the power and simulation runs. In fig.7.12 the graph is constant means that there is no variation in power with respect to the number of runs. However in fig.7.13 the output power varies with number of runs. At first the power decreases with increasing the dispersion coefficient and then goes on increases.

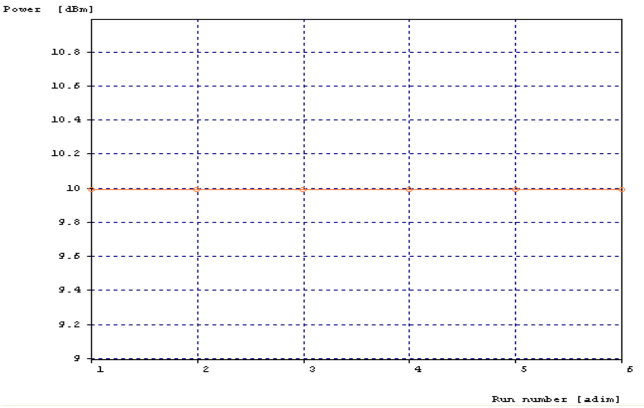


Fig.7.13. Input power

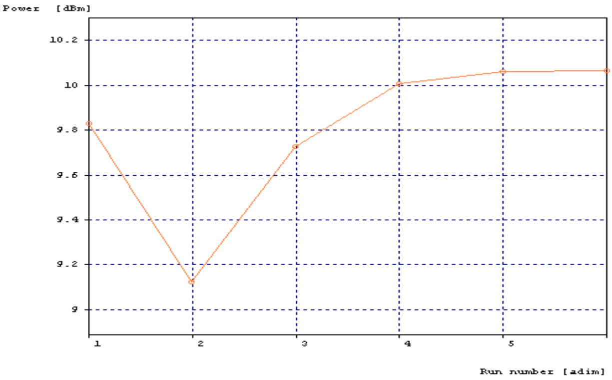


Fig.7.14. Output power

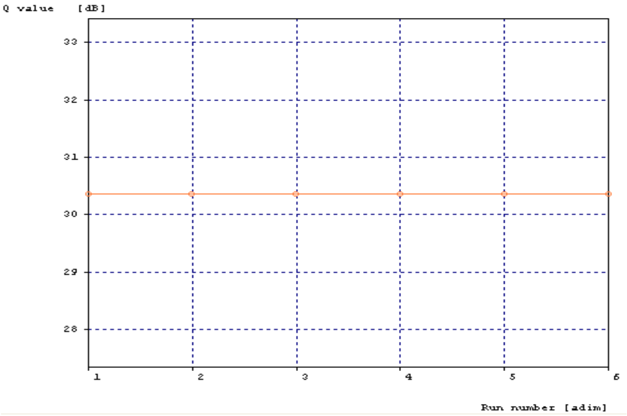


Fig.7.15. Q-factor of input wave

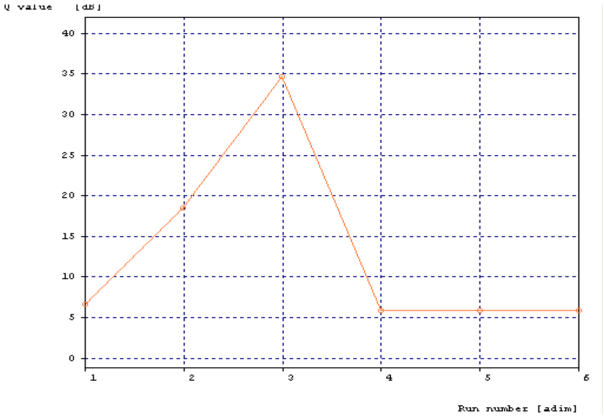


Fig.7.16. Q-factor of output wave

Similarly in fig.7.14 and 7.15 the graphs of Q factor versus the number of runs, for input and output wave have been shown respectively. As discussed earlier, the self phase modulation effect is minimum at D=-2 ps/nm-Km. It can be seen in fig.7.15. also that the Q-factor increases to maximum at D=-2 ps/nm-Km and then goes on decreasing with increasing dispersion coefficient.

7.4 Conclusion

This chapter shows the design and implementation of a self phase modulation limited system. A 10 Gbps NRZ signal is sent over four fiber spans of 100Km each. Dispersion is completely compensated to isolate the SPM phenomenon. Dispersion values have been varied from -10 to10 ps/nm-Km through the parametric run feature. The power at the fiber input for each span has been set to 10 dBm. EDFA noise has been turned off. By decreasing the dispersion modulus, SPM grows and depletes the signal. In passing from the normal to the anamolous dispersion regime, the received optical spectrum at first widens and then narrows.

CHAPTER 8

PERFORMANCE LIMITATIONS OF WDM OPTICAL TRANSMISSION SYSTEM DUE TO CROSS- PHASE MODULATION IN THE PRESENCE OF CHROMATIC DISPERSION

With the increasing demands on the capacity of wavelength division multiplex (WDM) systems, nonlinear effects including inter-channel crosstalk become increasingly important. One of the most significant nonlinear effects is cross-phase modulation (XPM) and accurate determination of this effect is an important issue in the design of WDM optical system. In this chapter, the XPM effect has been presented. Simulation results for intensity fluctuations due to XPM in an intensity modulated-direct detection (IM-DD) WDM optical transmission system at bit rate of 10 Gbps are shown.

8.1 Introduction

Cross-phase modulation can be used as a technique for adding information to a light stream by modifying the phase of a coherent optical beam with another beam through interactions in an appropriate non-linear medium. This technique is applied to fiber optic communications. In DWDM applications with intensity modulation and direct detection (IM-DD) the effect of XPM is a two- step process: First the signal is phase modulated by the co propagating second signal. In a second step dispersion leads to a transformation of the phase modulation into a power variation. Additionally the dispersion results in a walk-off between the channels and thereby reduces the XPM-effect.

8.2 Simulation setup and description

The simulation setup for a pump- probe configuration for NRZ modulated WDM system at 10 Gbps is shown in Fig.8.1. This simulation is carried out to observe the effect of XPM in a pump-probe configuration in the presence of CD. The different simulation parameters used in simulation are shown in Table.1. Two WDM channels are launched over two DS fiber spans of 100 Km each. Dispersion is compensated at each span to better show the cross phase modulation phenomenon. Fiber dispersion is varied from 0 to 4ps/nm-Km through parametric runs. In order to focus on cross phase modulation, one of the two channels-the “probe” – has a low power and is sent along the link together with a stronger “pump” channel. This system consist of three sections i.e. transmitter section, fiber section and receiver section.

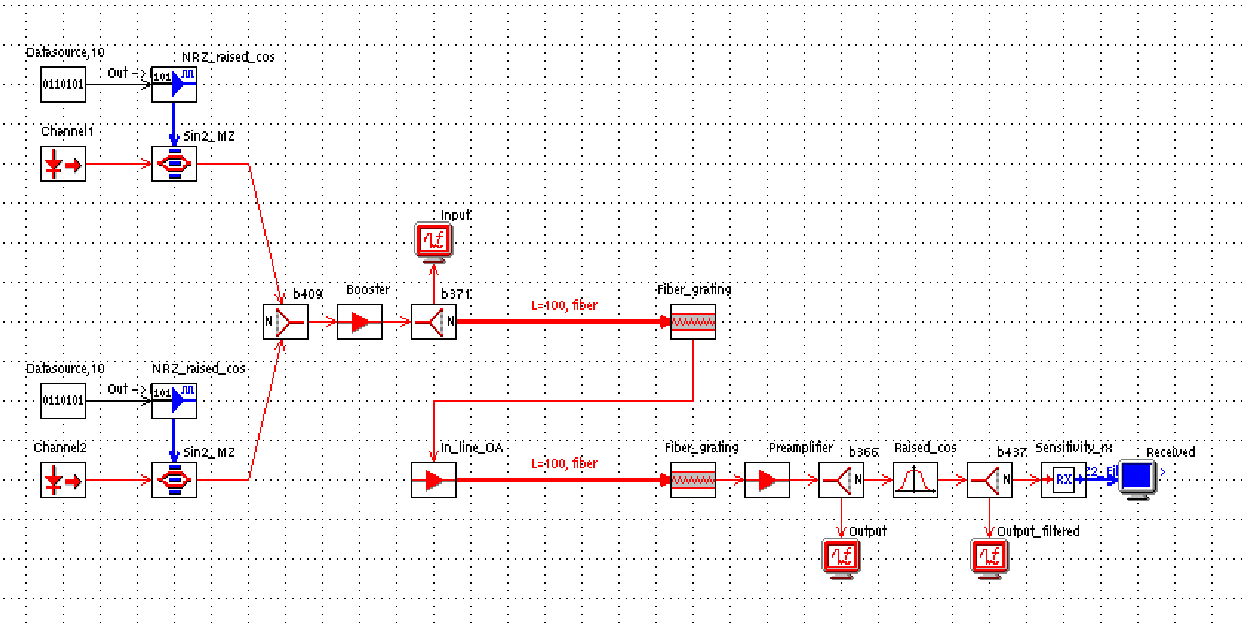


Fig.8.1. Simulation setup

A. <u>Transmitter block</u>

The transmitter consist of a data source which generates pseudo random bit sequence at the rate of 10 Gbps. This bit sequence is fed to NRZ coded signal. There are two channels high and low power channels to differentiate the input signals from each channel. The higher power channel named the pump channel produces phase modulation of the neighbouring channel. Cross phase modulation is advantageous over the SPM is because it has two channels with the same bit rate. The pump channel operates at a frequency of 193.075 THz which is equivalent to 1552.725 nm. The probe channel operates at 193.025 THz which is equivalent to 1553.127 nm. The two optical signals are then combined to form a single optical signal representing two signals

B. <u>Fiber channel</u>

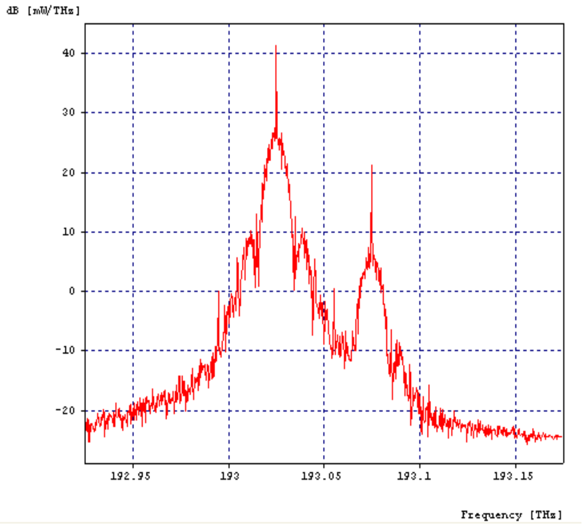
The combined optical signal is fed into the fiber which is a single mode DSF. The fiber model in optsim takes into account the unidirectional signal flow, stimulated and spontaneous Raman scattering, kerr nonlinearity an dispersion. Here, we can set the length, dispersion parameters, attenuation, nonlinear index, core area of the fiber and XPM options. The parameters are adjusted according to the simulation environment given in Table.1. At the output of the fiber, the probe signal would have undergone the XPM effects and the waveform at the output will be distorted.

C. <u>Receiver block</u>

Dispersed optical signal is transmitted through Cosine raised Gaussian filter which behaves as band pass filter as per the configuration of filter. The filter outputs the signal, by passing the frequencies specified in the filter block configuration.

8.3 Results and discussion

Signals from the two channels are combined with light wave to form an optical signal with respect to the each channel. The two optical signals are then combined to form a single optical signal representing two signals, which is shown in the Fig.8.2. The optical signal having two signals is carried to booster block to amplify the signal.



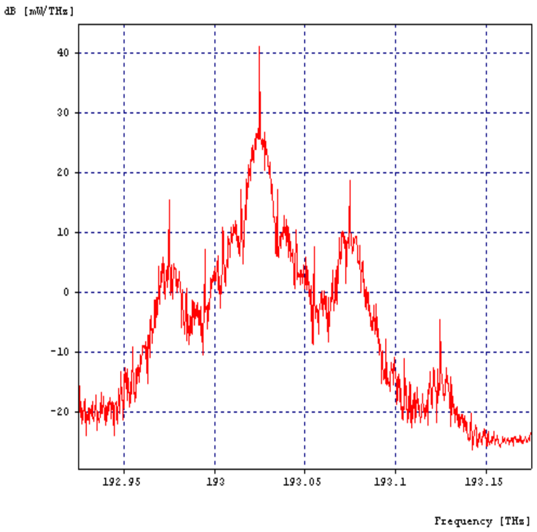


Fig.8.2. Optical signal from two different channels

Fig.8.3. Dispersed optical signal

The first signal seen in fig.8.2 is from high power channel and other is from low power mode channel. Fig.8.3 shows the signal dispersed due to the cross phase modulation effect over the fiber channel. The dispersed optical signal is transmitted through cosine raised Gaussian filter which behaves as band pas filter as per the configuration of the filter. The filter outputs the signal by passing the frequencies specified in the filter block configuration. The signal generated by band pass filter is shown in fig.8.4. This is sent to a sensitive receiver which converts the optical signal into electrical signal.

Fig.8.4 shows the output signal at dispersion coefficient D=0 ps/nm-Km which is obtained in the first run of simulation. Fig.8.5 shows the output signal at D=4 ps/nm-Km.

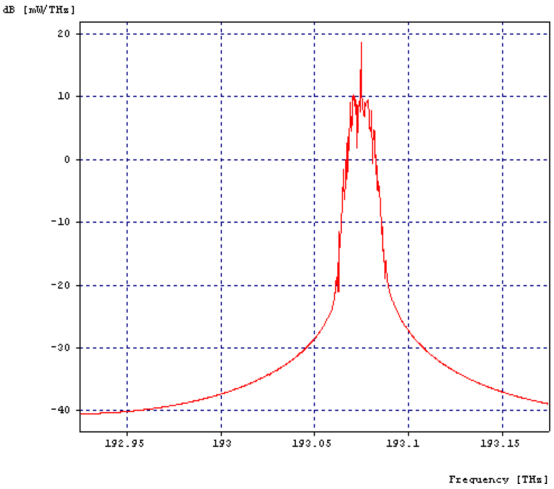


Fig.8.4. Output optical signal of XPM (with D= 0)

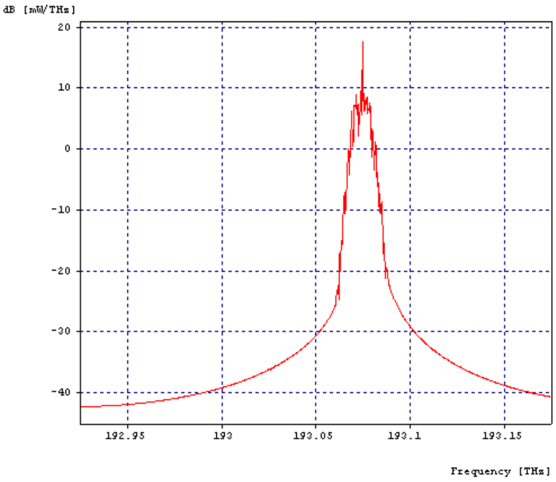


Fig.8.5. Output optical signal of XPM (with D=4)

It is observed that as we go on increasing the dispersion coefficient, XPM effect is decreased. This can be inferred from the eye diagrams also. Fig.8.6 and 8.7 shows the eye diagrams for the received signal at dispersion coefficient D= 0 and D= 4 ps/nm- km respectively

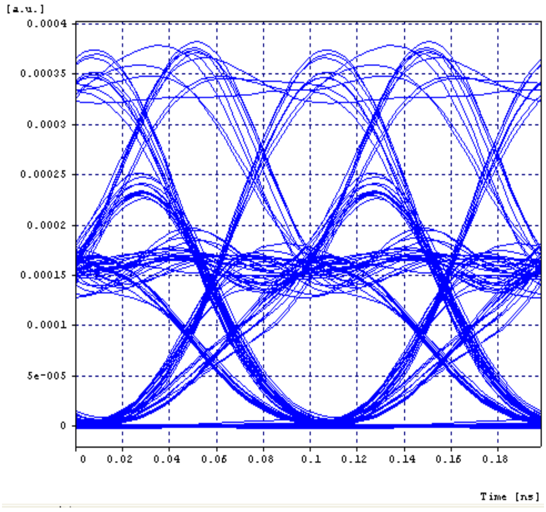


Fig.8.6. Eye diagram with dispersion coefficient D=0

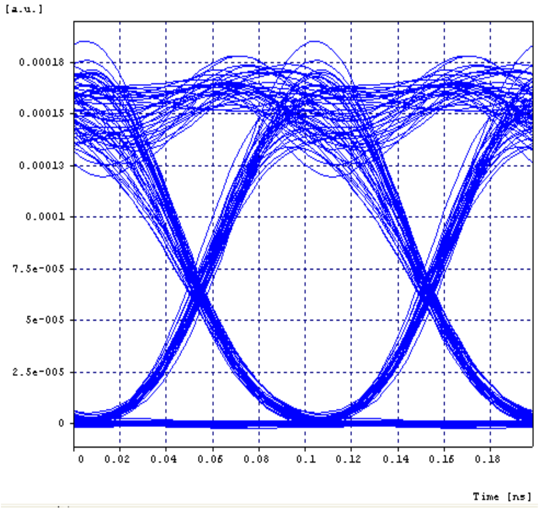


Fig.8.7. Eye diagram with dispersion coefficient D=4

Fig.8.8 and 8.9 shows the graphs of Q-factor and BER for fiber of length 100 Km. The graphs are plotted with respect to the dispersion coefficient. It can be seen that at zero dispersion coefficient, the Q-factor is very poor and BER is high. But as we go on increasing the dispersion coefficient, the quality factor goes on increasing and BER decreases.

Thus with an optimum amount of dispersion, the value of XPM is reduced to a great extent. This has been shown for a fiber of length 100 Km. When the length is increased or decreased, the Q-factor and BER values have the sane relation with the dispersion coefficient value.

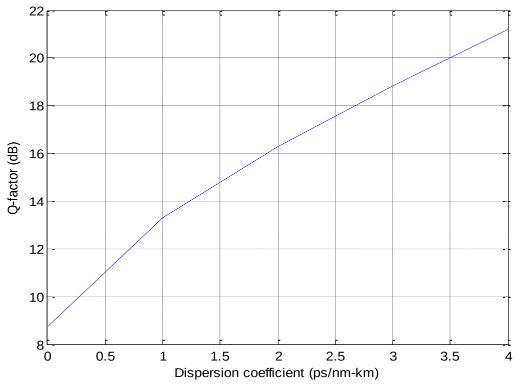


Fig.8.8. Q-factor for fiber of length 100Km

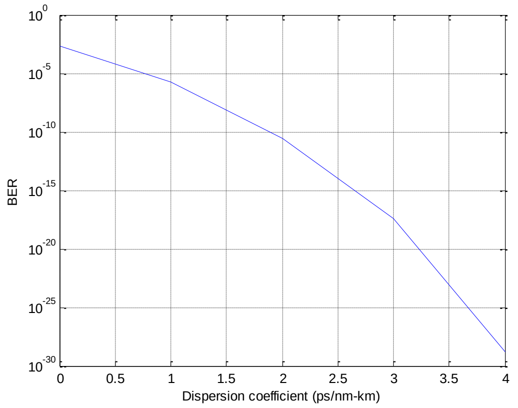


Fig.8.9. BER for fiber of length 100 Km

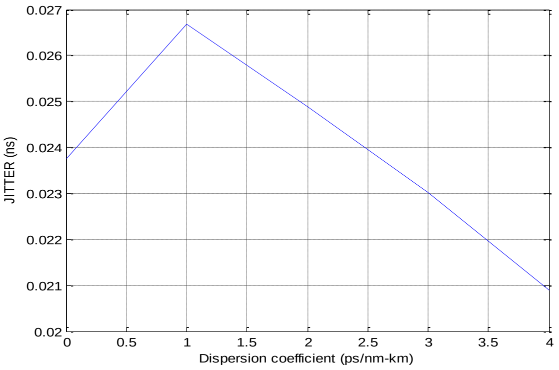


Fig.8.10. Jitter for fiber length 100 Km

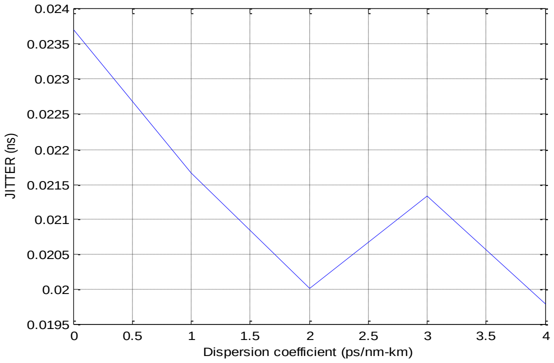


Fig.8.11. Jitter for fiber length 200 Km

Different plots of jitter have also been plotted with respect to dispersion coefficient.Timing jitter generated by transmitter and reciever devices is also one of the compotents when overall system performance is evaluated.Fig.8.10 shows the plot of jitter with respect to dispersion coefficient for 100 km fiber. Fig.8.11 and 8.12 shows the jitter for fiber lengths 200 km and 50 Km respectively.

It is observed that for 100 Km fiber, there is a jump in the jitter as the dispersion coeffiecient is increased upto 2 ps/nm-Km, and then again the jitter decreases. For fiber lengths 200 Km and 50 Km the jitter value has an abrupt decrease at 2 ps/nm-Km.

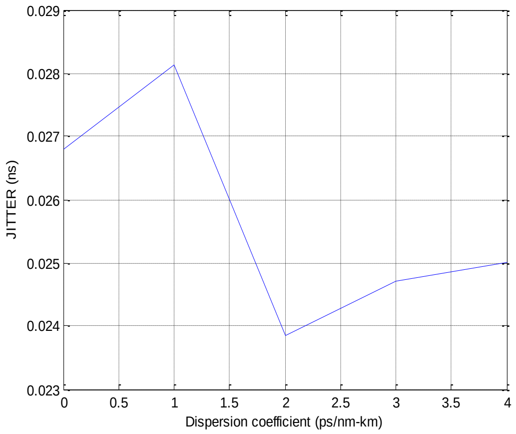


Fig.8.12. For fiber of length 50 Km

8.4 Conclusion

In this chapter, a design of XPM limited system is shown. The simulation is carried out to observe the effect of XPM in a pump probe configuration in the presence of chromatic dispersion. Results show that on increasing the dispersion, XPM reduces. This is shown in the output spectrum and the eye diagram. This effect is same as seen in case of FWM. Also, the Q-factor goes on increasing with increasing dispersion coefficient and BER decreases. This is found to be true for any length of the fiber as observed from the plots of jitter also.

CHAPTER 9

COMPENSATION OF CHROMATIC DISPERSION AND NONLINEARITY USING OPTICAL PHASE CONJUGATOR

9.1 Introduction

Fiber optic communication is a way of transmitting information from one place to another by sending light through an optical fiber [1]. When the signal is transmitted through long haul communication system (over fiber of distance typically larger than 100 Km), it get distorted. This distortion can be a result of fiber nonlinearities and dispersion. Three properties of optical fibers are dispersion, absorption and scattering which cause attenuation and also decrease in transmission power. The interplay between dispersion and nonlinearity causes the major transmission impairement in the optical systems [51-52]. Among many techniques to compensate dispersion and nonlinearities, OPC is found to be the most promising one [53-54]. Spectral inversion is done through OPCs and the most effective technique is mid span spectral- inversion (MSSI) [55-56]. This technique allows the simultaneous compensation of signal GVD and nonlinear effects [56], thus improving the system performance. In this chapter two designs have been described. In the first design, phase conjugator is placed in the middle of the fiber employing MSSI technique. The results were found to be accurate, but the length of the fiber is limited and on increasing the length, the signal gets distorted again. Moreover due to the presence of fiber losses, perfect symmetry cannot be obtained in common transmission system. A solution proposed in [57] requires placement of OPC at a specific position along the fiber cable which is not easily accessible in real systems. So designs using even and odd number of phase conjugators have been shown.

9.2 Optical phase conjugator

A. Optical phase conjugation technique

Consider a signal pulse with the optical carrier frequency ωi is transmitted through fiber 1 of length L1, with a frequency dependent propagation constant $\beta l(\omega)$.GVD causes the dispersion of the signal. The phase conjugated of signal pulse fp(t) with optical carrier frequency ωp is combined with the transmitted in fiber 2 of length L2 with propagation constant $\beta 2(w)$. Hence the dispersion is compensated at the receiver with the GVD encountered at fiber 2.

B. Midway OPC for optical fiber communication systems

The chromatic dispersion of an optical fiber system is defined as [58]

$$D(\lambda)= 1/L.d\tau/d\lambda= 1/L.d/d\lambda\ [-L\lambda_s^2/2\pi c(d\beta/d\pi)_{\lambda s}]= -\lambda_s^2/2\pi c(d^2\beta/d\lambda^2)_{\lambda s}$$

where, τ is the time delay for an optical pulse propagating in a single-mode fiber of length L,β is the propagation constant of the fiber, λs is the central wavelength of the optical signal, and c is the speed of light. For most standard single-mode fibers the zero-dispersion wavelength is $\lambda_{0\sim}1.3\mu m$ at which $D(\lambda_0)\sim 0$; in a signal wavelength region of $\lambda_s\sim 1.5\mu m$ the chromatic dispersion $D(\lambda_s)\sim(15\text{-}18)$ ps/km/nm. The chromatic-dispersion-limited transmission distance over this type of fiber (for a 1-dB penalty) is given by [59]:

$$B^2L= 6500\ (\text{Gbps})^2\ \text{Km}$$

Here B is the bit-rate and L is the fiber length. The limit, for example, is B65km at a bit-rate of 10 Gbps. In addition to the limitation from chromatic dispersion, there is another limitation that is related to the spectral broadening of optical pulses propagating in a fiber system. It is known that an optical fiber is a good third-order nonlinear medium, in which many nonlinear optical effects can easily take place. Among these effects, the light-intensity dependent refractive-index change may produce self-modulation of an intense short light pulse during its propagation in the fiber system. Sequentially, this self-modulation effect leads to a spectral self-broadening of the given light pulse.

Some other nonlinear processes, such as four-wave mixing or stimulated scattering may also produce new spectral components or cause further spectral broadening. This kind of spectral broadening may degrade the quality of signal transmission and particularly impose a limitation on the minimum spectral spacing between two adjacent channels in a fiber communication system adopting WDM regime. Optical phase conjugation (OPC) technique can be successfully employed to overcome the limitations from chromatic dispersion and self-modulation (spectral self-broadening) respectively. In this case a special optical phase conjugator is placed in the middle of two identical single-mode fiber transmission systems, which generates phase-conjugate waves of the input signal waves with an inverse spectral structure. This special technique adopted for fiber communications is called ‘‘midway optical phase conjugation (MOPC)’’ or ‘‘mid-span spectral inversion (MSSI). The principle of this technique is based on the theoretical proposal reported by Yariv et al. in 1979 [43].

9.3 Simulation setup and description

The simulation is done using optsim software to demonstrate the effect of OPC in compensating chromatic dispersion and nonlinear effects. Figure 9.1 and 9.2 shows the block diagrams and optical transmission system with and without OPC.

In fig.9.1, a continuous wave laser is used as source with power level to 9 dBm and bit rate of 10 Gbps is sent through fiber with dispersion 16 ps/nm-Km. A standard single mode fiber of length 200 Km is used. Fiber in both the cases is not ideal i.e. fiber characteristics such as other nonlinearities is considered. Attenuation property of fiber which is dependent on its length is also assumed to be zero. PIN photodiode is used at the receiver.

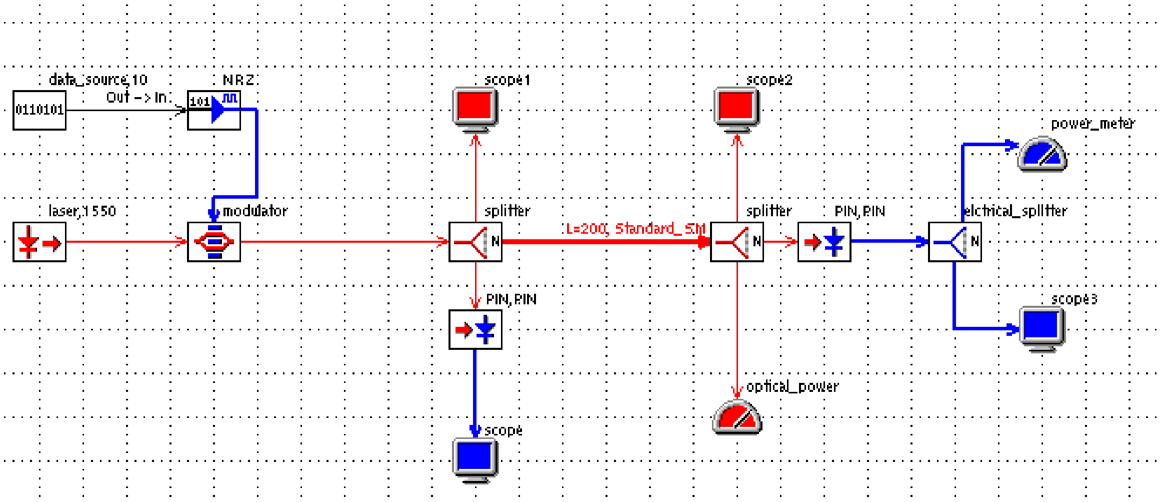


Fig.9.1. Simulation setup for an optical transmission system having laser source with wavelength 1550nm and power 9 dBm, fiber length 200 Km with dispersion 16 ps/nm/Km and without any optical phase conjugator

The simulation set up in fig.9.2 shows the use of optical phase conjugator block as an efficient way to compensate dispersion and non linearities. A 10 Gbps data stream is sent over a lossless fiber link where dispersion is set to D=16 ps/nm-km. The transmitted optical peak power is substantially higher (9 dBm). This power increase causes non-linearity effects become important. After 100 Km, the eye diagram shows a completely closed eye, due to the accumulation of chromatic dispersion and fiber non-linearity effects. After phase conjugator and another 100Km long fiber link, the received eye is completely open even in this case where there are also the fiber non-linearity effects.

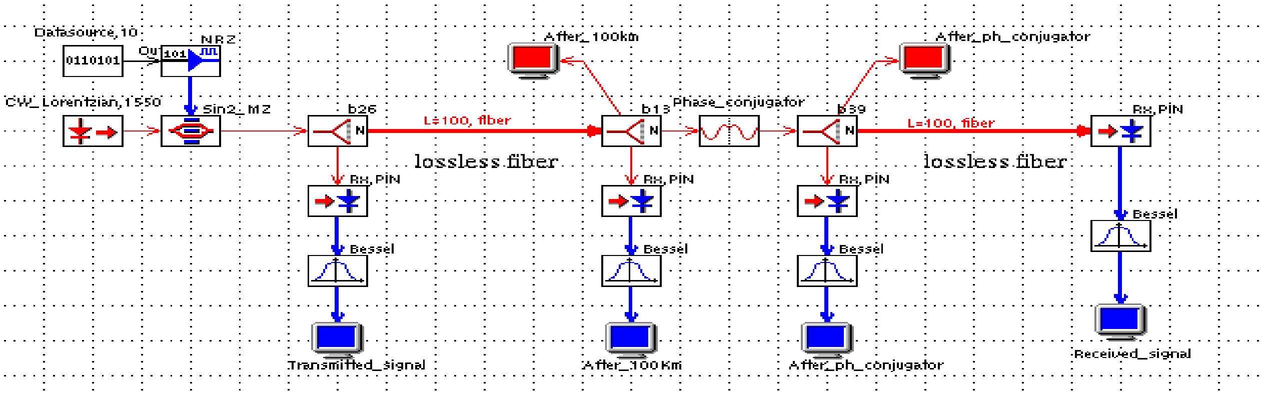


Fig.9.2. Simulation setup for an optical transmission system having laser source with wavelength 1550nm and power 9dBm, fiber length 200 Km, dispersion 16ps/nm/Km and with optical phase conjugator at the midway of the fiber

In the system shown above, includes a first fiber, phase conjugator and a second fiber. The first fiber transmits a light signal which is a signal obtained from the transmitter. The phase conjugator recieves the light signal from the first fiber and produces a phase conjugated light signal. The second fiber recieves the phase conjugated ligth signal from the first finer and produces a corresponding conjugated light signal. This is the basic principle in a midway placed OPC.

Further the simulation setup is extended by increasing the number of optical phase conjugators. Figure 9.3 and 9.4 shows the Simulation blocks for even and odd number of OPCs

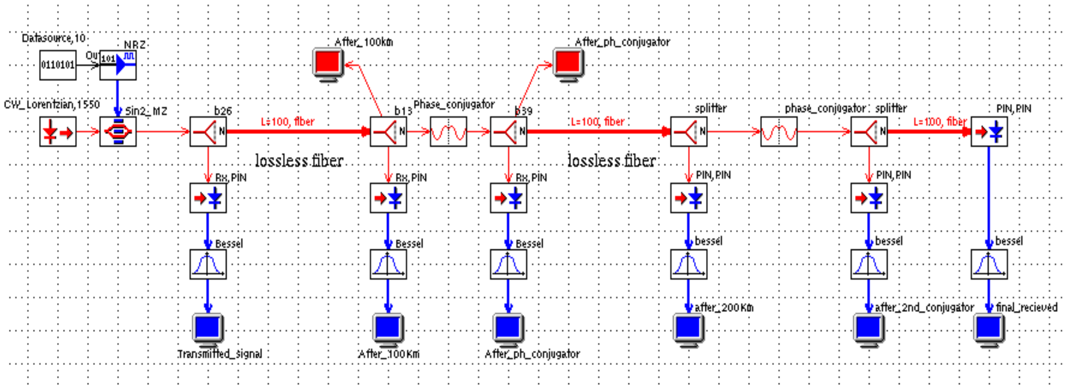


Fig.9.3. Simulation setup for optical system using even number of phase conjugators

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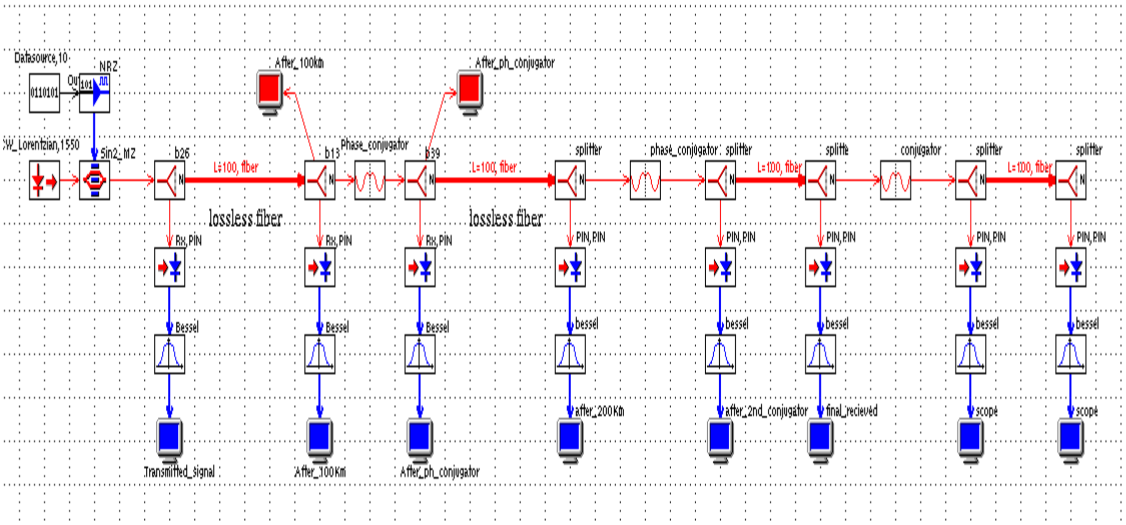

Fig.9.4. Simulation setup of optical system using odd number of phase conjugators

9.4 Results and discussion

Figure 9.5 and 9.6 shows the eye diagrams of output and input waves when OPC is not used. Distortion due to chromatic dispersion and nonlinearities can be clearly seen in the output waveform.

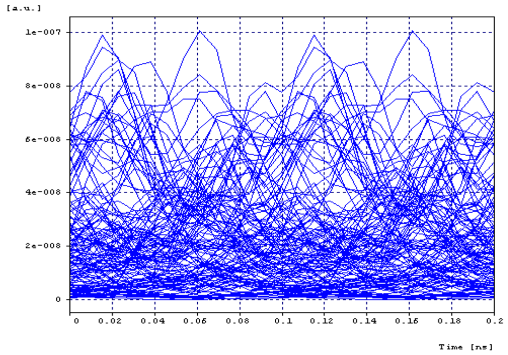

Fig 9.5.Eye pattern at the receiver after 200Km without OPC

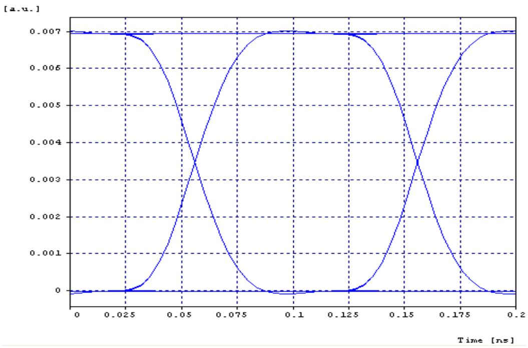

Fig.9.6. Eye patten of the input wave

Figure 9.7 and 9.8 shows the results for the simulation setup employing OPC in midway of the optical fiber. It can be seen from the eye diagrams that there is a huge improvement in the waveform and the received eye is completely open.

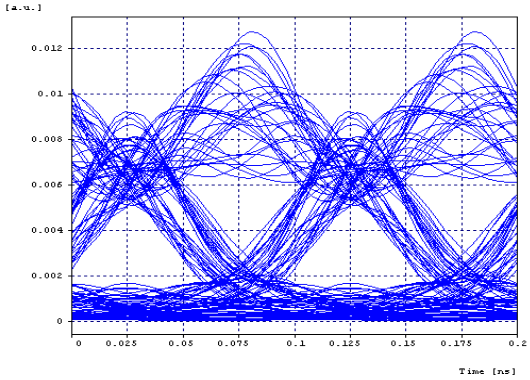

Fig.9.7. Distorted wave after 100Km

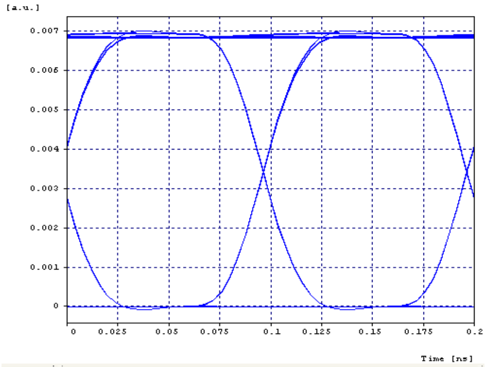

Fig9.8. Phase conjugated wave after 200Km

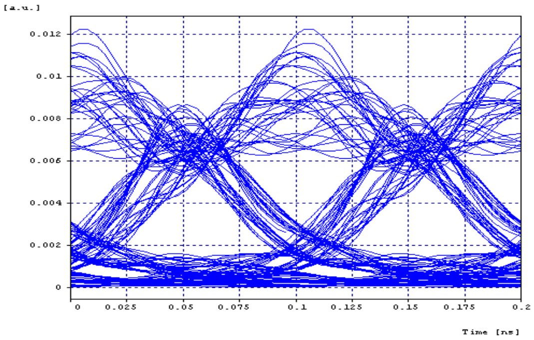

Fig.9.9. Output of the system using even number of phase conjugators

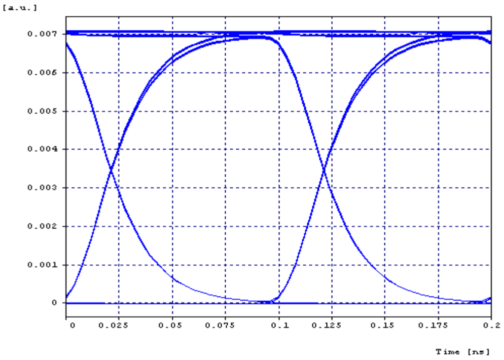

Fig.9.10. Output of the system using odd number of phase conjugator

9.5 Conclusion

In this chapter, the compensation of nonlinearities along with dispersion has been demonstrated. For simulation, a dispersed medium is used and the power is kept high so as to introduce nonlinear effects in the fiber. It is shown that the nonlinearities can also be compensated along with dispersion by using MSSI technique in which an OPC is placed in the mid-way of the fiber. However a limitation with this system is that it cannot be used for long haul transmission systems (i.e. fiber length greater than 1000 Km). The simulation is done for different lengths of fiber and is it is found that the signal distortion due to both the effects is compensated effectively upto 200 Km. after this again there are distortions in the signal. Further the number of OPCs to be used effectively in case of long haul communication has been demonstrated. Results show that by using odd number of OPCs for any length of fiber will compensate the dispersion and nonlinearities effectively.

CHAPTER 10

CONCLUSION AND FUTURE SCOPE

This chapter summarizes the conclusions that can be drawn from research performed for this thesis and then provide suggestions for future research.

10.1 Conclusion

The first objective of this is to investigate the four wave mixing effect on various channel spacings. Comparison of four wave mixing effect at different channel spacings revealed that 75 GHz spacing has the edge over 6.25 GHz spacing. It is found that the spacing of 75 GHz has the lowest BER. Secondly on comparing the performance of a WDM system by changing different transmitter components, it is found that FWM is minimized when RZ rectangular modulator driver is used and the system is independent of the bit rate of data source. The performance analysis of system limited by SPM, XPM and FWM is also done. This is carried out in the presence of chromatic dispersion. Results show that on increasing the chromatic dispersion, some nonlinearities can be minimised upto some extent. FWM goes on decreasing by increasing dispersion coefficient upto 4 ps/nm-Km. SPM is reduced greatly at dispersion coefficient of -2 ps/nm-Km. XPM also decreases as the dispersion coefficient is increased. So an optimum level of chromatic dispersion in the fibers is suggested for minimization of both the effects. However the interplay between nonlinearities and dispersion causes the major distortion when dispersion is not optimum. So various methods have been studied for their simultaneous compensation. Out of which, MSSI technique using OPC is presented. It is found thata by using OPC; dispersion is compensated upto a great extent even in the presence of nonlinearities. However a limitation with this system is very long haul transmission system. In this case the OPC units need to be repeated. So two designs are proposed, one using even number of OPCs and the other using odd numbers. Results show that out of these, systems using odd number of OPCs for any length of fiber will compensate the dispersion and nonlinearities effectively.

10.2 Future scope

- The thesis work is limited to FWM, XPM and SPM. The variations in BER, Q-factor, eye opening and output spectrums of systems limited by four wave mixing on changing the channel spacing and various components have been considered. The effect of changing these parameters for SBS and SRS can be studies.

- Also the effect of these nonlinearities in the presence of chromatic dispersion can be studied.
- The practical implementation of the designs presented has to be done on a hardware kit
- Various methods to optimize chromatic dispersion has to be explored.
- Methods have been presented to reduce the nonlinear effects, the various applications of these nonlinearities can be studied.
- Various other techniques for the compensation of nonlinearities is to be studied.

REFERENCES

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