Analysis of Fiber Nonlinearities in WDM Fiber Optic Transmission System by Varying Different Parameters

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Abstract: ***Capacity of optical transmission system can be increased either by using the technique of wavelength division multiplexing (WDM) or by increasing the bit rate of transmission. But with the increased bit rates and launched optical powers the nonlinear optical effects increases. Ultra fast third order susceptibility is reason behind Non Linear Effects whose real part leads to Self Phase Modulation (SPM), Cross Phase Modulation (XPM) and Four Wave Mixing (FWM) and imaginary part contributes to Stimulated Raman Scattering (SRS). SPM converts optical power fluctuations into phase fluctuations in single channel which eventually degrades the signal. XPM causes interference by phase shifts which depend on intensity between two optical fields. This effect limits the input optical power and capacity of the system. Dominating effect of WDM system is FWM. SRS causes unwanted power tilt which reduces optical signal to noise ratio. Performance degradation and channel crosstalk of the system can be induced in multi channel systems by these nonlinearities. In this paper the effects of input power, bitrates, dispersion and various other parameters are observed on nonlinearities using OPTSIM 5.2 software. The results are shown through Quality Factor and Eye diagram.***

Index Terms: ***FWM, Non Linear effects (NLE), SPM, SRS, XPM.***

I. INTRODUCTION

Optical fiber is a physical transmission medium applied for high speed data communications. Optical networks are adopted for efficient accommodation of traffic. Information is send from one place to another in the form of light pulses. Today's fiber optic data systems are very complex, expensive and lossy. Increasing demand of communication requires robust and efficient optical system. Due to possibility of high transmission capacity WDM system is progressing. Multiple data signals of light wavelength are transmitted by WDM systems. WDM is the most popular method to increase the capacity of a single strand of fiber. Traditionally, only one color of light was used in a single strand of fiber to carry the information such as 1550nm light[8]. However, starting from the early 1990s, the internet boom pushed service providers to find a method to increase the capacity of their network, which is when WDM devices were invented[6][7]. In a WDM system many different colored lights are combined by a WDM multiplexer and put into a single strand of fiber, each color is a separate channel. At the receiver, each color is separated into its own channel by a WDM de-multiplexer device. It is known that a single fiber's capacity is increased by 40 times with a 40-channel WDM. The advantage of WDM is that we only need to upgrade the end equipment; there is no need to increase the branches of fiber, which is much more costly.

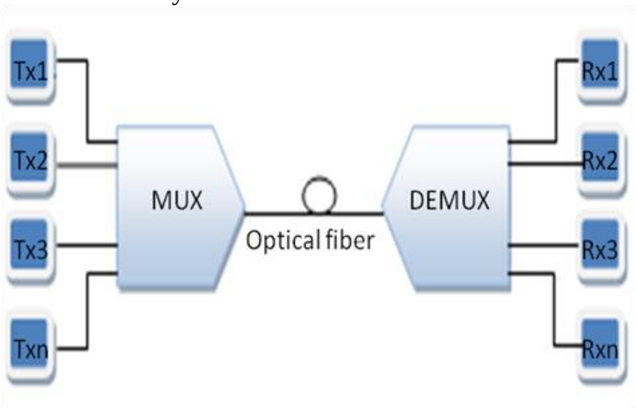

Figure 1: WDM System

The main drawbacks of physical medium are non linear effects, dispersion and loss. For long haul optical fiber communication system performance is influenced by fiber non-linearity which accumulates along the length of optical fiber. Non linear effects occur where interaction of signal at different wavelengths is possible. Nonlinearities result in distortion, attenuation and interference in optical system which degrades system performance[5]. The most important non-linear effects are Four-wave mixing (FWM), Stimulated Raman Scattering (SRS), Self Phase Modulation (SPM) and Cross Phase Modulation (XPM)[3]. Phase of the signal is affected by SPM and XPM which causes spectral broadening which in turn increases dispersion. In fiber optic channel, the widening of pulse duration leads to dispersion which limits transmission rate and bit spacing.

II. THEORY

In a non-linear fiber optic system the medium properties are altered by the signal itself. The refractive index is related to the intensity of light; let us assume that the refractive index increases with the intensity of light. It means that the whole pulse is not going to see the same propagation parameters because at the center of the pulse, light is intense and the refractive index seen by pulse is different than the edge of pulse where light is less intense, because of that refractive index is lesser compare to the pulse refractive index seen at the center. When the non linear effects are present in the optical fiber even any small perturbation will break this signal into pulses.

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Therefore, without considering the pulse nature of the signal the nonlinear propagation will not be high. When the electric field is imposed on a dielectric material there is induced polarization which is given by the susceptibility of the medium and for approximation we consider the first order susceptibility which gives the dielectric constant of the medium. However, if the intensity of light is large then the first order term is not adequate and we also have to consider higher order terms into the polarization of the material. In general, the induced polarization in the material is given below:

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

In the above equation, the first term is dominant and contributes to the dielectric constant. The second term shows that the dielectric constant has an effect of electric field itself. The third term which is the third order susceptibility says that the refractive index is proportional to square of the electric field and this term contributes to the nonlinear effects. In the presence of nonlinearities, according to the Kerr effect the refractive index is given as,

$\bar{n}(\omega, |E|^2) = \bar{n}(\omega)+n_2|E|^2$

The first term is the linear term and second term is the nonlinear term, n_2 is the material dependent nonlinearity coefficient. This coefficient is related to the third order susceptibility of the medium. When light enters the optical medium it keeps interacting with optical fiber therefore we have a cumulative effect of nonlinearities at the output.

In fiber optic technology the nonlinear Schrodinger equation is given as[1]:

$\partial A/\partial Z - j(\beta_2/2)(\partial^2 A/\partial T^2) + (\alpha/2)A = -j\gamma|A|^2A$

The optical fiber is governed by the above equation. It gives the evolution of the pulse[4]. The second term of the above equation gives the dispersion.

Here, $\beta_2 = \partial^2\beta/\partial\omega^2$

This change in group velocity as a function of frequency shows dispersion. The right hand side of the equation gives nonlinearity. The nonlinearity operator ($\hat{N}$) is solved in time domain.

$\hat{N} = -j\gamma|A|^2$

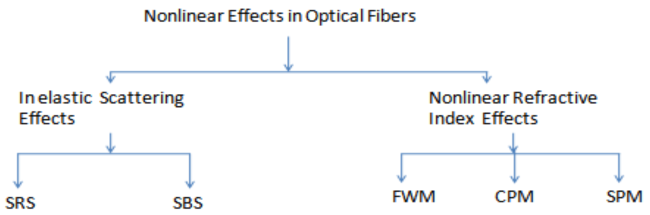
The nonlinear length is given by:

$L_N = 1/\gamma P$

The dispersion length is given by:

$L_D = T_o^2/|\beta_2|$

Considering physical length of fiber different combinations are possible. When $L<<L_D$, $L<<L_{NL}$, fiber is just a medium to transfer light. When $L>>L_D$, $L<<L_{NL}$, pulse broadening phenomenon takes place by dispersion. When $L<<L_D$, $L>>L_{NL}$, the nonlinear effects such as SPM, XPM, FWM and SRS are visible. At this point pulse will encounter different refractive indices at different locations.



Within the pulse the frequency will travel with different velocities which create phase function. The change in phase is created by the pulse itself hence the phenomenon is known as SPM. It does not change the envelope of the pulse but each frequency undergoes phase change which is nonlinear as a function of time. So, this modifies the spectrum of the pulse. In particular for WDM system, one of the most impacting phenomenons is Cross Phase Modulation (XPM). Whenever there is sufficient power in each channel then the phase of signal changes with respect to another signal resulting in XPM. When n channels are transmitting then they will affect the power of (n-1) channels.Nonlinear change of phase due to variations of power in adjacent channels can strongly affect system performances. A noisy perturbation due to XPM will limit capacity and distance.

The interactions between 3 wavelengths produce a 4^{th} wavelength in WDM system, resulting in FWM[2]. FWM is caused by the dependence of refractive index on the intensity of the optical power. If three signal waves with frequencies $\omega_i,\omega_j,\omega_k$ are incident at the input of the fiber the nonlinear susceptibility of the fiber generates new waves at the frequencies $\omega_i\pm\omega_j\pm\omega_k$[9] where ω_i,ω_j and ω_k need not necessarily be distinct. The most troublesome one is the signal corresponding to $\omega_{ijk}=\omega_i+\omega_j-\omega_k$.This is because depending on the individual frequencies this beat signal may lie on or very close to one of the individual channels resulting in significant crosstalk to that channel.

When two laser beams with different frequencies propagates together through an optical fiber, the longer wavelength beam experiences optical amplification at the expense of the shorter wavelength beam[10]. Due to difference in the frequencies, lattice vibrations are produced which leads to rise in temperature. When these vibrations are associated with optical phonons, the effect is called Raman Scattering. It is detrimental for intense pulses in optical fiber devices. It can transfer most of the signal energy into the wavelength range where laser amplification does not occur. This limits the maximum signal power.

III. SIMULATION SETUP

A. Self Phase Modulation

First block in this section is a pseudo random signal generator, next is the electrical driver used to convert binary sequence into electrical pulses. Bessel or "Maximally flat delay" filters are implemented as shown in figure 2. Booster is a fixed output power optical amplifier which stimulates an EDFA (Erbium Doped Fiber Amplifier). Optical spectrum analyzer estimates the input spectrum by partitioning the total data sequence into various sections. The channel consists of optical fiber and in line amplifier. Receiver section starts with a fixed EDFA as preamplifier followed by raised cosine optical filter. Optical spectrum analyzer is used to access the non-linear output optical spectrum. Next component simulates a PIN photodiode. The visualization tool known as scope collects data on various diagrams such as eye diagrams, amplitude and power spectrum.

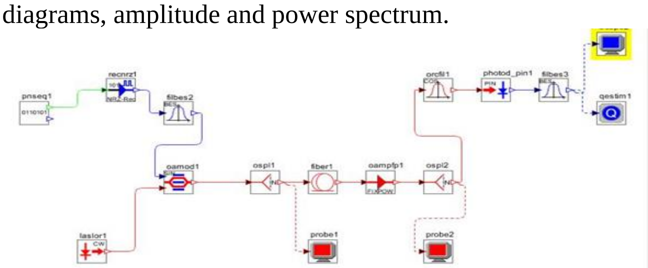


Figure 2: Self Phase Modulation

B. Cross Phase Modulation

The XPM is analyzed for two channel system as shown in figure 3 and dispersion is varied from -4ps/nm/km to 4ps/nm/km. The transmitter section comprises data source, laser source, modulator driver and modulator. The transmitted signal is formed by modulating the light carrier with the NRZ data source.The combined optical signal is fed into the single mode fibre. Parameters such as attenuation, nonlinear index, core area of the fiber can be set. At the output of the fiber the waveform will be distorted due to XPM.The PIN diode is used in receiver as a detector. The output of the receiver is given to the measurement devices which are fed through the electrical splitter, the electrical scope and the Q estimator. Performance degradation of the system will directly affect the eye diagrams.

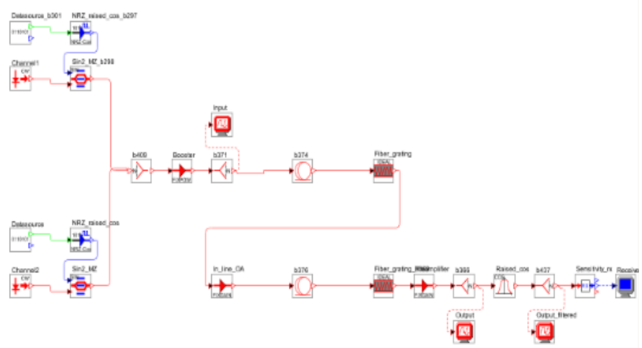


Figure 3: Cross Phase Modulation

C. Four wave Mixing

To transmit data, 8-channel WDM system is implemented over a distance of 500 km. All the components such as modulators, filters, laser diodes required to build the optical network are provided by optsim software. In the presence of chromatic dispersion the effect of FWM is observed in WDM system. PRBS generator generates pseudo random bit sequence at bit rate of 10 Gbps. Single mode fiber is used to combine all optical signals. At the fiber output waveform will be distorted as signal would have experienced the FWM effects. Optical band pass Bessel filter followed by sensitivity receiver is used in receiver section as shown in figure4. Optical signal is converted in to electrical signal by a photodiode in sensitivity receiver. Q factor, BER, eye display is estimated from optical and electrical oscilloscope. There is no crosstalk if the eye opening is very wide.

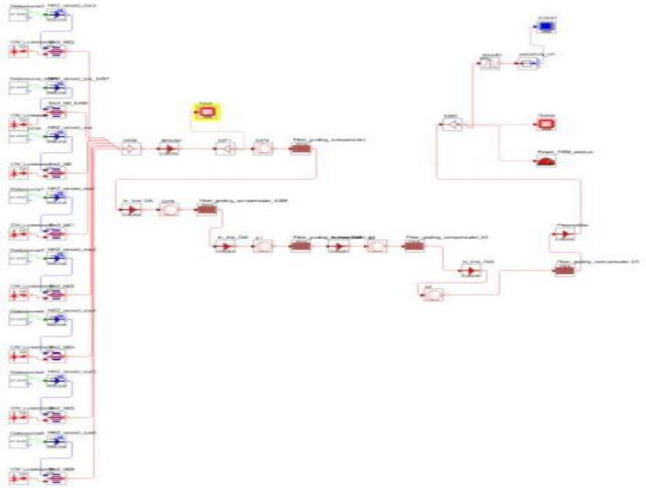


Figure 4: Four Wave Mixing

D. Stimulated Raman Scattering

The transmitter section consists of two subsystems as shown in figure 6 and figure 7. When high intensity optical input power is encountered in the fiber, the SRS effect will occur. Due to the SRS effect, the minimum power that could be sent through the fiber is reduced. The SRS effect is observed by varying input power and by varying the number of channels. In the figure shown we have considered 4 wavelength channels with an equal power of 10mW (10dB) and equal channel spacing. These channels are given to the Multiplexer. Power booster is used to amplify the signal. The channel consists of single mode fiber. At receiver we have used scope to see the output power spectrum and measure the power tilt.

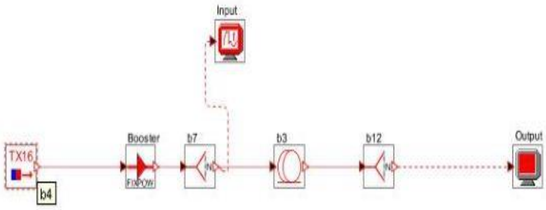


Figure 5: Stimulated Raman Scattering

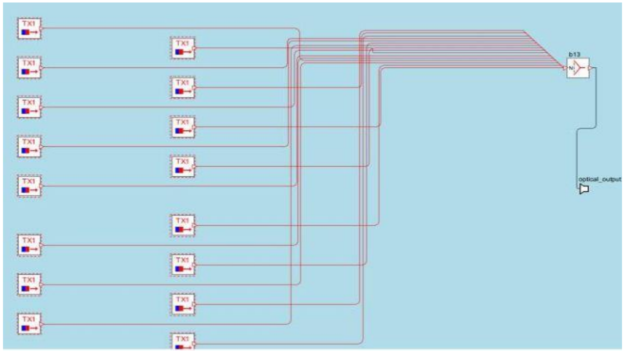


Figure 6: Transmitter Subsystem I

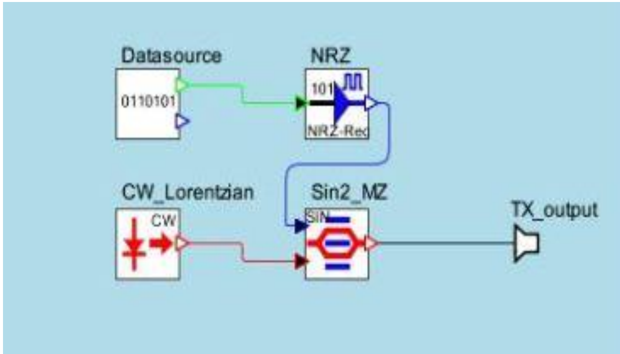


Figure 7: Transmitter Subsystem II

IV. RESULTS AND DISCUSSION

A. Self Phase Modulation

The effect of SPM for different parameters such as length of fiber, bit rates, center emission frequencies, dispersions and booster powers has been investigated. Increasing the length of the fiber causes a decrease in the Q factor (as shown in table I). Increasing Bit rate causes increase in the Q-factor which leads to spectral broadening and thus degrades the signal quality (as shown in table II and figure 8).

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As we increase the centre frequency, Q value and eye opening decreases. Also, the output power decreases which degrades the signal and displaces the side bands (as shown in table III).

Length of fiber (km)	Power (dbm)	Q factor (db)
20	10.004	34.442
30	9.964	30.56

Table I

When the preamplifier power is varied, Q factor is found to increase slightly and the eye closure happens to decrease. It is worth noting here that if the input power is increased, the preamplifier power is found to decrease (as shown in table IV).Output spectrum analysis for preamplifier powers of 10mW and 15mW is shown in figure 9. Increasing dispersion value drastically degrades the Q factor value as shown in table V. Increasing input power up to some extent causes some degradation which increases considerably if the input power is further increased (as shown in table VI).

Parameter under observation	bit rate	
	10 Gbps	15 Gbps
Q value (in dB)	29.73	29.04
Eye closure (in dB)	0.2614	0.2746
Eye opening (in dB)	0.0155	0.0153

Table II

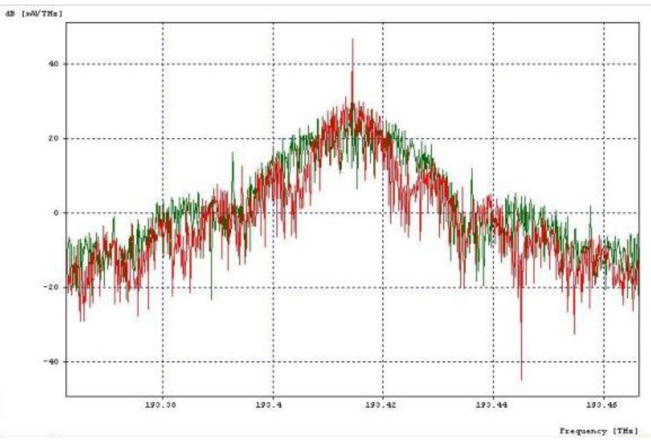

Figure 8: Spectral Broadening

Parameter under observation	Frequency		
	193 THz	193.02 THz	193.04 THz
Q value (in dB)	26.929	26.808	26.73
Eye closure (in dB)	0.4847	0.494	0.558
Eye opening (in dB)	0.273x10-2	0.2573x10-2	0.238x10-2
Output power (in dBm)	9.942	9.696	9.373

Table III

Parameter under observation	preamplifer power	
	10mw	15mw
Q value (in dB)	26.95	26.96
Eye closure (in dB)	0.479	0.478
Eye opening (in dB)	0.273x10-2	0.273x10-2

Table IV

Parameter under observation	Dispersion	
	-5ps/nm/km	10ps/nm/km
Q value (in dB)	37.394	36.116
Eye closure (in dB)	0.0895	0.1256
Eye opening (in dB)	0.01676	0.01680
Output power (in dBm)	10.053	10.080

Table V

Parameter under observation	Input power variation		
	10mw	13 mw	17mw
Q value (in dB)	32.04	30.31	7.31
Eye closure (in dB)	0.2732	0.428	17.22
Eye opening (in dB)	0.357x10-2	0.256x10-2	0.121x10-4
Output power (in dBm)	9.878	9.415	8.919

Table VI

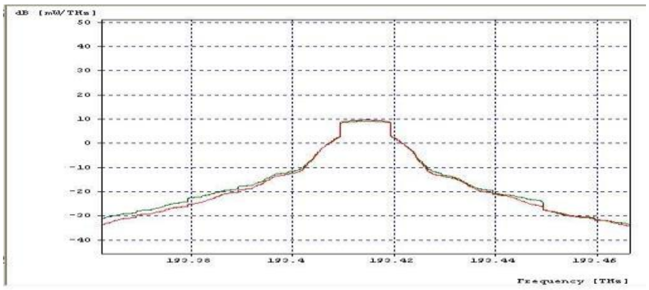

Figure 9: Spectral Analysis for Pre-Amplifier Powers 10mW and 15 mW.

B. Cross Phase Modulation

Eye diagrams and Q-factor for the different values of optical dispersion is shown below. As the values of dispersion vary, nonlinearities also vary in the optical fiber, which gives result to Cross Phase Modulation (XPM).Input and output spectrum is shown in figure 10 and figure 11.

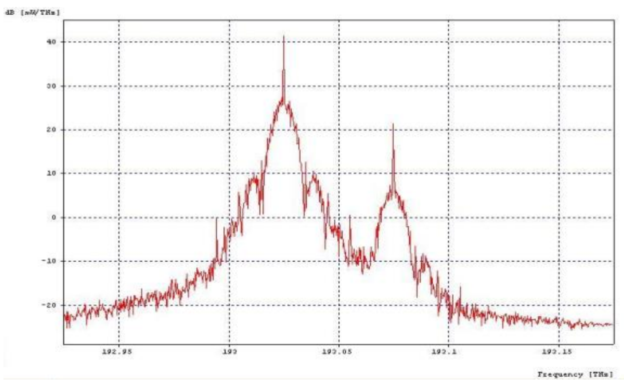

Figure 10: Input Spectrum

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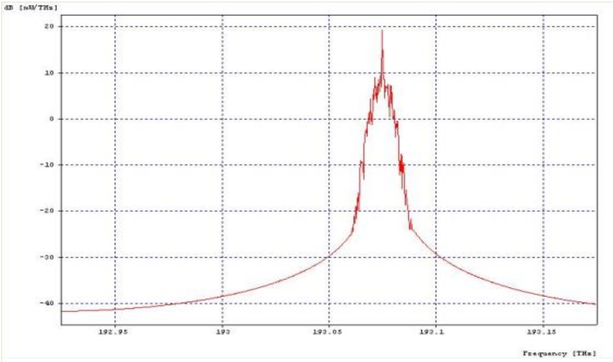

Figure 11: Output Spectrum

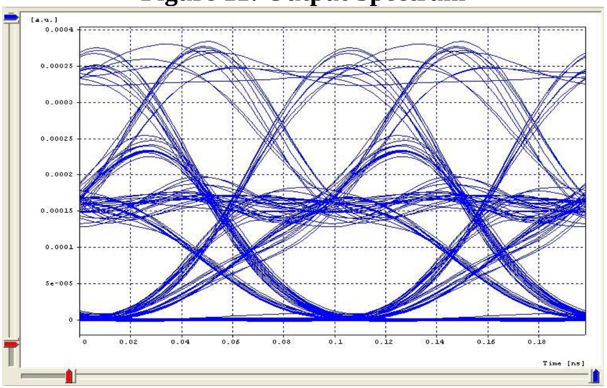

Figure 12: Eye Diagram at 0ps/nm/km

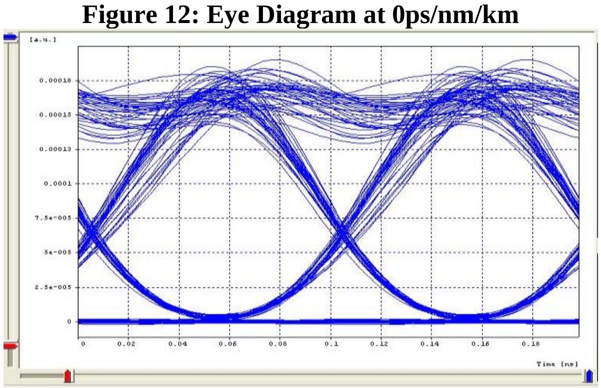

Figure 13: Eye Diagram at -1ps/nm/km

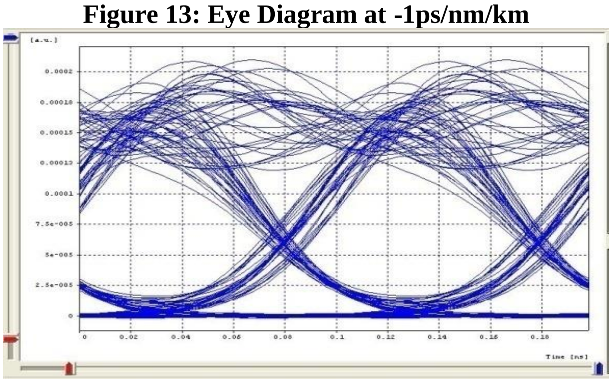

Figure 14: Eye Diagram at -3ps/nm/km

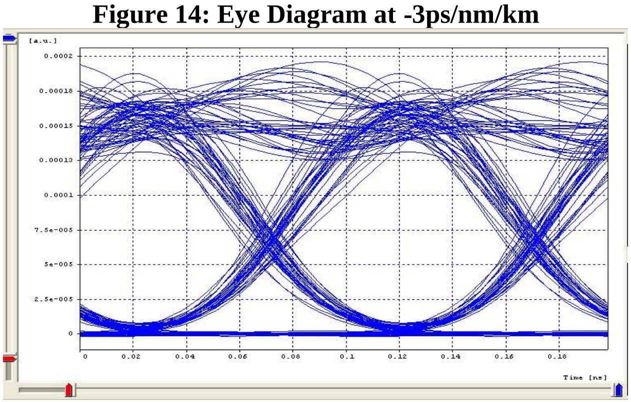

Figure 15: Eye Diagram at 3ps/nm/km

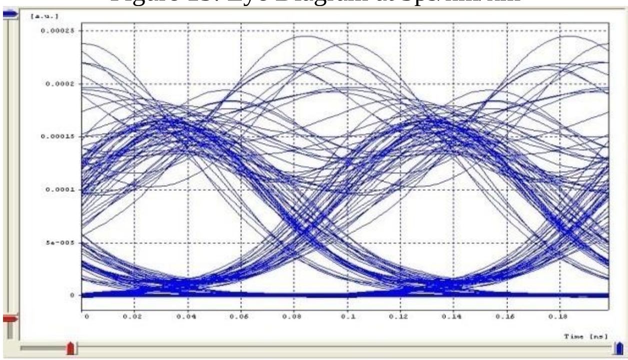

Figure 16: Eye Diagram at 1ps/nm/km

Results show that the Quality Factor becomes nonlinear due to Cross Phase Modulation (XPM). We can reduce the Cross Phase Modulation up to some extent but at higher bit rates we are still not able to remove the Cross Phase Modulation completely, which is a challenge for various scientists in the optical fiber field. The effect of XPM is expected to be smaller in systems operating at higher dispersion coefficients. We have shown that the XPM effect is highly dependent on dispersion coefficient of the fiber.

C. Four Wave Mixing

The effect of FWM on WDM system is investigated in terms of eye diagram, BER, Q-factor etc by varying the dispersion coefficient. The channels are separated by 25 GHz and modulated at 10 Gbps data rate. The distance between the in-line optical EDFA fibre amplifiers is 100 km (span length). The fibre dispersion value is varied from 0 ps/nm-km to 8 ps/nm-km. The frequency range from 192.90 THz to 193.25THz is provided to eight channels. They have uniform spacing of 0.05 THz. The signal is examined to investigate the effect of FWM using optical power meter with a centre frequency 193.025 THz. Eye diagrams show the effect of FWM at 0 ps/nm-km and 8 ps/nm-km for equal channel spacing. The fibers which have higher value of dispersion are good enough than the zero dispersion fibre for a WDM fibre-optic transmission system..The eye diagrams at dispersion coefficient 0ps/nm-km and 8ps/nm-km are shown in figure 17 and figure 18.

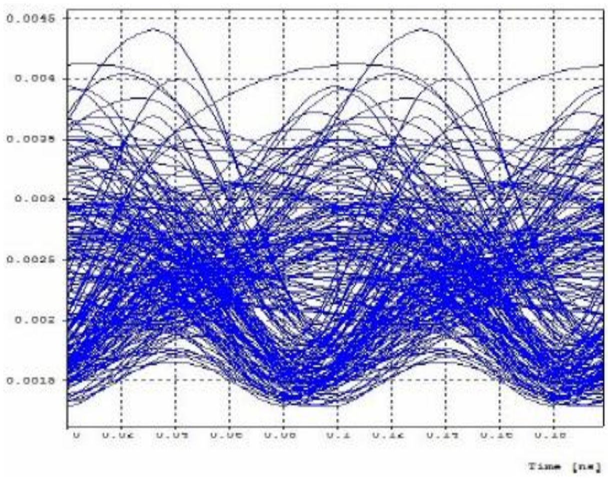

Figure 17: Dispersion at 0ps/nm/km

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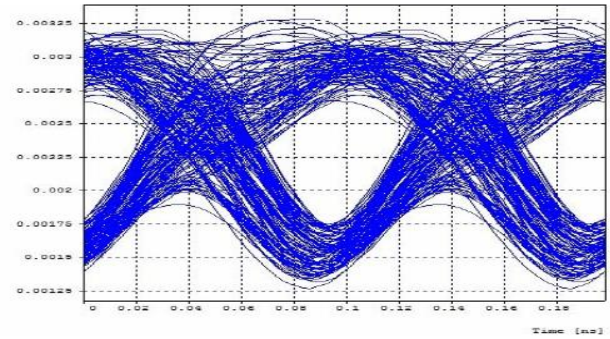

Figure 18: Dispersion at 8ps/nm/km

At bit rate of 10 Gbps, the effect of dispersion coefficient on FWM in 8 channel WDM system is shown. It is observed that FWM effect can be suppressed by increasing dispersion in the fiber. The effect of FWM cross generation is maximum at zero dispersion. Energy transfers from main component to new component as FWM component increases. High level of interferences and performance degradation is caused because of direct overlapping of these components with original signal.

D. Stimulated Raman Scattering

For a 16-channel WDM system the output power spectrum at an input power of 10mW with Raman crosstalk is shown in figure 19.The value of power tilt is found to be 24.1dB.When the input power is increased to 15mW the power tilt increases to 26.9649dB as shown in figure 4.2.The analysis of power tilt at various input powers for a 4-channel and 16-channel WDM system is shown in table VII.

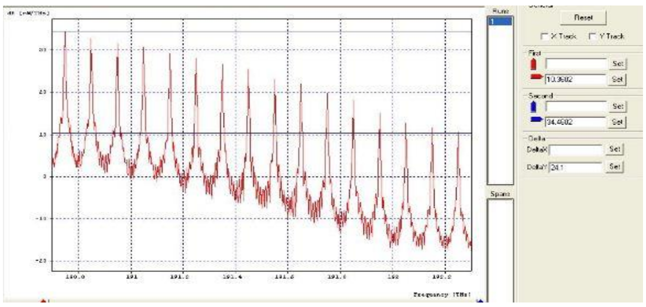

Figure 19: Power tilt at 10mW

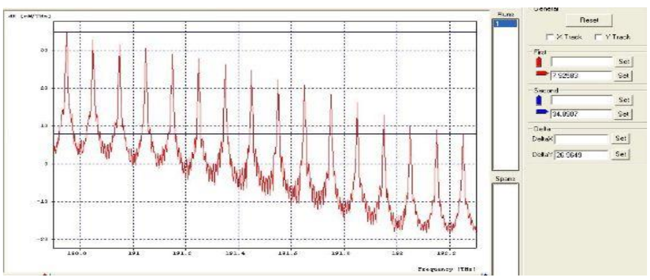

Figure 20: Power tilt at 15mW

Input Power (dBm)	No. of channels	Power Tilt (dBm)
0	4	3.01
	16	21.1129
10	4	4.86
	16	24.1
15	4	5.2
	16	26.9649

Table VII

V. CONCLUSION

The In this paper we have demonstrated the effects of dispersion coefficient, length of fiber, input power, bit rate, center emission frequency, and booster power on FWM, SPM, XPM and SRS in WDM system. While analyzing it is found that the effect of FWM is suppressed by increasing the value of dispersion coefficient. It is found that at zero dispersion, the effect of FWM is maximum and the effect decreases as we increase the value of dispersion. A detailed analysis of SPM shows that Q factor decreases with increase in length of fiber, bit rate, dispersion value, increase in input power and Q factor increases with slight increase in pre-amplifier power. It is observed that with an increment in pre-amplifier power input power decreases. XPM effect is analyzed in a 2-channel WDM system. XPM limits the system capacity and input power. The effect of XPM is maximum at high bit rate and low dispersion coefficient.SRS effect occurs when high intensity input power is allowed in single mode fiber. By decreasing input power the SRS can be minimized. A decrease in input power will decrease the power tilt. The effects of XPM, SPM,FWM and SRS on WDM system can be optimized by choosing appropriate values of different parameters in optical fiber communication systems.

REFERENCES

1. G. P. Agrawal, “Fiber-Optic Communication Systems”, 3rd edition(2002), pp 64-67,280-281.
2. Singh,S.P.,Kar,S.,Jain,V.K.“Performance of All-optical WDM network in presence of Four-Wave Mixing,Optical Amplifier Noise,and Wavelength Converter Noise” Volume 26,Issue 2,2007 pages 79-97.
3. Jing Liang,Student Member and Katsushi Iwashita,”FWM compensation in DPSK transmission by reducing detectors with digital coherent detection using backward propagation,” International Journal of Information and Electronics Engineering, Vol. 1, No. 1, July 2011.
4. Nasrin Sultana and M. S. Islam “Analysis of XPM Effect with SPM and GVD in WDM Fiber Optic Transmission System,” ICCCE 2012, 3-5 July 2012, Kuala Lumpur, Malaysia.
5. Kyo Inoue, “Four-Wave Mixing in an Optical Fiber in the Zero-Dispersion Wavelength Region,” Journal of lightwave technology, Vol. 10, No. 11, November 1992 1553 .
6. Y. Miyamoto, A. Hirano, K. Yonenaga, A. Sano, H. Toba, K. Murata, O. Mitomi, “320 Gbit/s (8 × 40 Gbit/s) WDM transmission over 367 km with 120 km repeater spacing using carrier-suppressed return-to-zero format”, Electron.Lett., vol. 35, pp. 2041- 2042, 1999.
7. S. P. Majumder, A. Azhari and F. M. Abbou, “Impact of fiber chromatic dispersion on the ber performance of an optical cdma IM/DD transmission system” IEEE Photon Technol. Lett., vol. 17, pp. 1340–1342, 2005.
8. Zheng,X., Liu,F.,and Jeppesen,P.: “Receiver optimization for 4Gb/s optical duobinary signal”,IEEE Photonics Technol. Lett., 2001, 13,(7)
9. Prabhpreet Kaur, Kulwinder Singh,” Analysis of Four Wave Mixing Effect at Different Channel Spacing in Multichannel Optical Communication System”, IJEIT Volume 3, Issue 5, November 2013
10. T.Sabapathi., S.Sundaravadivelu and Prabha. G, “Analysis and Reduction of Stimulated Raman Scattering in DWDM Fiber Optic Communication System”, Int. Conference in Cape Institute of Technology, May 2010.

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