

Comparative Analysis of Nonlinear Transmission Impairments in WDM Optical Network

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Abstract— Non-linear effects are always the major degrading sources that occur in nonlinear optical materials such as photonic switch, optical fiber cable. Such interaction between waves causes interaction between channels. FWM (Four Wave Mixing) is one of the major degrading factors in WDM (Wavelength Division Multiplexing) optical network along with other fiber non-linearity. SPM (Self Phase Modulation) is a non-linear effect of light-matter interaction. XPM (Cross Phase modulation) and SRS (Stimulated Raman Scattering) are the major degrading factors in WDM optical network which causes cross talk and makes the system least effective. Due to which it is important to investigate the impact of FWM, SPM, XPM and SRS on the design and performance of WDM optical network. In this paper, the effects of FWM with dispersion and polarization, the effects of SPM with dispersion and power, the effects of XPM with dispersion and the effects of SRS with ASE (Amplified Spontaneous Emission) noise being analyzed and simulated on OPTSIM. The length of fiber being taken is 150KM. The simulation results of Input/Output spectrum gives the measure of non-linear variation.

Index Terms— Dispersion, FWM, Polarization, Power SPM, SRS, XPM,

I. INTRODUCTION

WDM is widely used for optical communication networks and systems in to being utilize the maximum bandwidth available for the transmission. The fiber non-linearities result in severe degradations on the performance of optical communication systems [1]. The non-linearity in optical fibers falls into two categories such as: Inelastic Stimulated Scattering and Kerr Effect.

Stimulated Scatterings such as Raman and Brillouin are responsible for the intensity dependent losses or gains. It is being generated due to stimulated processes. Kerr effect happens due to the change of the refractive index of the fiber with the intensity of the transmitted signal, due to which the signal suffers phase modulation. The nonlinear refractive index is responsible for intensity dependent phase shift of the optical signal. One of the major difference between scattering effects and the Kerr effect is that stimulated scattering have threshold power levels at which the nonlinear effects manifest themselves while the Kerr effect doesn't have such a threshold. Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Four Wave Mixing (FWM) are generated due to optical Kerr effect. FWM is the major

degrading factor in WDM optical communication systems [2]. FWM is one of a broad class of harmonic mixing or harmonic generation process, in which three or more waves combine to generate a wave of different frequency that is the sum or difference of the signals that are mixed and generate a fourth EM wave because of the fiber's third order nonlinear susceptibility. FWM is an intermodulation phenomenon in the non-linear optics, where the interactions between two wavelengths produce two extra wavelengths in the signal. It is similar to the existence of third-order intercept point in electrical systems.

FWM is a weak effect, but it accumulates, if the signals in the optical channels remain in phase with each other over long transmission distances. Pulses transmitted over different optical channels, having different wavelengths, they will stay in the same relative positions along the length of the fiber because the signals experience near-zero dispersion [3]. This further magnifies at zero dispersion wavelength. FWM gives birth to new waves of the frequency:

$$f_{ijk} = f_i + f_j - f_k$$

For a WDM system with N channels the number of four-wave mixing products i.e. M is given as:

$$M = \frac{1}{2}(N^3 - N^2)$$

Here N is number of channels transmitted.

Thus in FWM effect, three co-propagating waves (N=4) produce nine new optical sideband waves (M=24) at different frequencies. This new frequency falls in the transmission window of the original frequencies that leads to severe cross talk between the channels propagating through an optical fiber. Moreover, the degradation becomes more severe for large number of WDM channels having small channel spacing.

Self-phase modulation (SPM) is a nonlinear optical effect occurring due to light-matter interaction. It is caused when an ultra-short pulse of light, during its travel in a medium, will lead to induce a varying refractive index of the medium due to the Kerr effect [4, 5]. This variation in refractive index leads to produce a phase shift in the pulse, further leading to a change of the pulse's frequency spectrum. SPM is an important effect in optical systems that use intense pulses of light, such as lasers and optical fiber communications networks [6].

In WDM system, the most impacting phenomenon is Cross Phase Modulation (XPM). Cross-phase modulation (XPM) is a nonlinear optical effect where one wavelength of light can affect the phase of another wavelength of light through the optical Kerr Effect. Fiber nonlinearities due to Kerr effect are a limiting factor for optical network. Nonlinear phase changing due to power variations in adjacent channels can strongly impact system performances. In IMDD systems where information is being coded on field amplitude and phase does not appear to be relevant, there is a phase-to-amplitude conversion due to dispersion is present [7,8]. During propagation a noisy perturbation due to XPM will accumulate together with ASE noise and other impairments limiting capacity and distance. XPM leads to an interaction of laser pulses in a medium. This is the basis of a scheme for Quantum Non Demolition (QND) measurements. This effect can be used for synchronizing two mode-locked lasers by using the same gain medium, in which the pulses being overlapped and experiences cross-phase modulation. In optical fiber communications, XPM in optical fibers can lead to problems with channel cross-talk. Cross-phase modulation is also sometimes mentioned as a mechanism for channel translation.

SRS is the inelastic scattering of photons. When photons being scattered from an atom or molecule, most photons are elastically scattered, that is the scattered photons have the same energy as the incident photons. A very small fraction of the photons (approximately 1 in 10 million) are scattered by an excitation, while with the scattered photons having a frequency different from and being lower than that of the incident photons [9]. More recently, the SRS has been used for optical amplification in optical telecommunications in distributed or discrete signal amplification. Even if discovered many years ago and highly investigated in the past, applications of Stimulated Raman Scattering (SRS) presented a renewed interest for compensation of optical losses in fibers transmissions, for the development of new tunable laser sources [10] or for low noise amplification of optically carried radiofrequency signals.

II. SIMULATION TOOL (OPTSIM)

This simulation tool (OPTSIM) provides support for multiple parameter-scans-based optimizations. It is the only design tool with multiple engines implementing both the Time Domain Split Step and the Frequency Domain Split Step for the most accurate and efficient simulation of any optical link architecture. MATLAB® interface makes it easy to develop custom user models using the m-file language and/or the Simulink® modeling environment. Interfaces with laboratory test equipment such as Agilent and Luna to merge simulation with experiment. Interfaces with device-level design tools such as Beam PROP and Laser MOD provide a powerful mixed-level design flow for optoelectronic circuits and systems. Application Programming Interface (API) for programming languages such as C/C++ for the development of custom user models. Best Fit Laser Toolkit™ makes

customizing powerful rate-equation laser model parameters to fit desired performance characteristics easily. Extensive library of predefined manufacturer components makes it easy to model commercially available devices. Intuitive and flexible measurement post-processing graphical interface acts like a virtual laboratory instrument.

III. SIMULATION OF FWM

A model of WDM optical communication network for dispersion is simulated using OPTSIM to illustrate the non-linear variations in FWM as shown in Fig.1. In this two WDM channel transmitter is required at the input side. WDM transmitter is composed of following blocks: data source, driver, laser source and amplitude modulator. The output of transmitter is applied to the optical combiner with attenuation on each output 0.91515dB. Then this output is connected to the booster having output power of 4mW or 6.0206dBm. Booster is an optical amplifier fixed output power device. This output of booster is connected to optical splitter through which input optical spectrum analyzer is being connected. In the input spectrum analyzer number of spectrum points over the simulation are 3000. This splitter output goes to the fiber link which is of 150KM in length and length statistical variation is 0.0, then this output of fiber link is connected to fiber grating compensator. In this ideal fiber grating compensator is used which compensates the fiber dispersion at each span. The output of fiber grating meets with the In-line optical amplifier which is a fixed gain amplifier. Gain for In-line optical amplifier is 30dB, then this is further connected to optical fiber of length 150km and ideal fiber grating compensator having reference frequency of 193.05THz and reference wavelength of 1552.9264 nm which is further in connection with Pre-amplifier of gain 30dB and optical splitter whose attenuation of each output is 0.91515dB. This splitter output is connected with output spectrum analyzer which has 1500 number of spectrum points over the simulation.

Two WDM channels transmitter

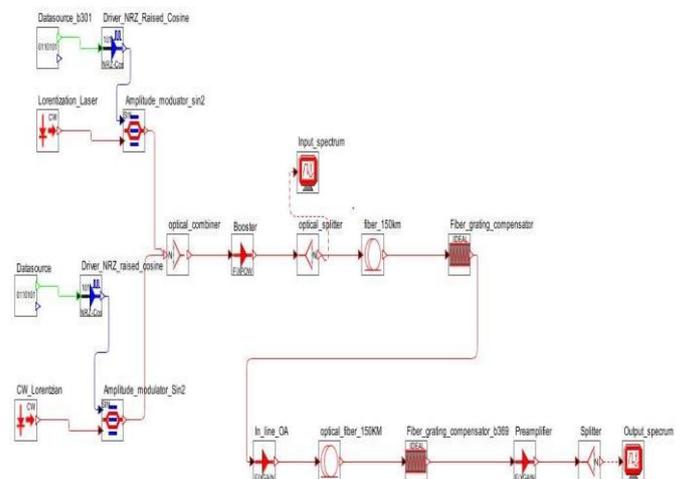


Fig.1 Simulation Diagram for FWM with Dispersion

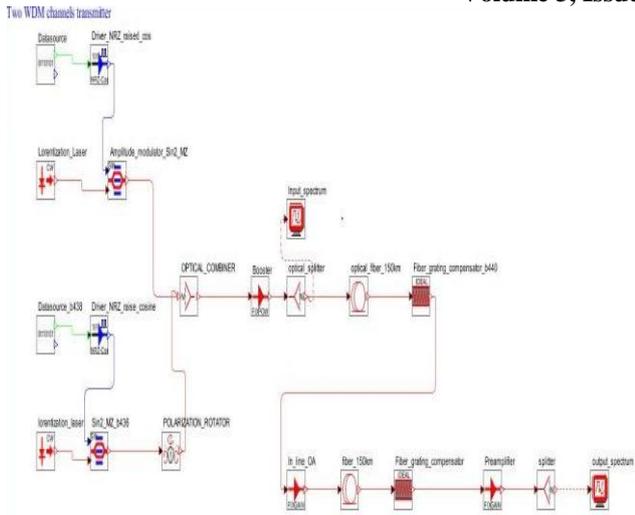


Fig.2 Simulation Diagram for FWM with Polarization

A model of WDM optical communication network for polarization is simulated using OPTSIM to illustrate the non-linear variations in FWM as shown in Fig.2. In this two WDM channel transmitter is required at the input side. WDM transmitter is composed of following blocks: data source, driver, and laser source and amplitude modulator. Polarization rotator of having number of polarization=1 and 1st Rotation="Axis-S2" is applied at the output of the amplitude modulator.

A. Simulated Results of FWM with Dispersion as well as with Polarization

Two WDM channels are launched over two DS fiber spans of 150KM, each Dispersion is completely compensated at each span. The results are quoted in Fig.3 (a), Fig.3 (b) and Fig.3(c). Fig.3 (a) shows optical power spectrum at the fiber input in the range of 192.90THz to 193.20THz. Fig.3 (b) shows the optical power spectrum at the output for different setting of dispersion in the range of 192.90THz to 193.20THz. The spectrum of the superimposed signals of input spectrum and output spectrum clears that FWM products decrease with increasing dispersion in the range of 192.90THz to 193.90 THz as shown in Fig.3(c).

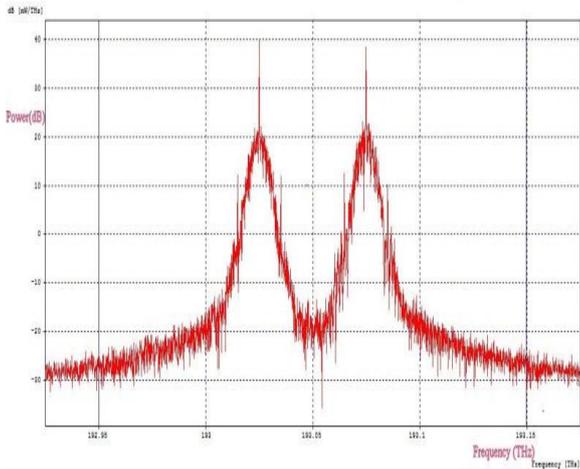


Fig.3 (a) Input Optical Spectrum

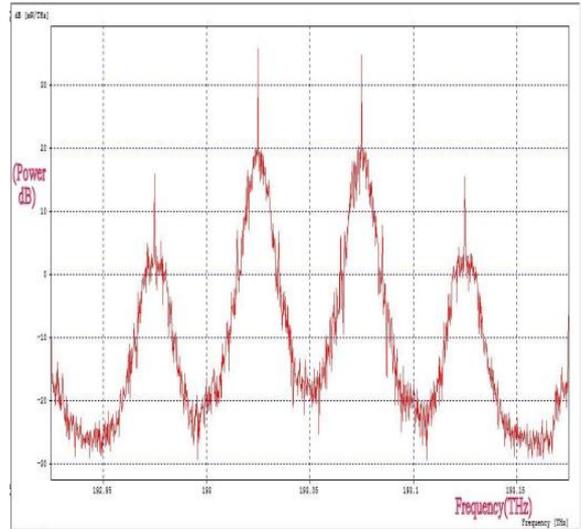


Fig.3 (b) Output Optical Spectrum

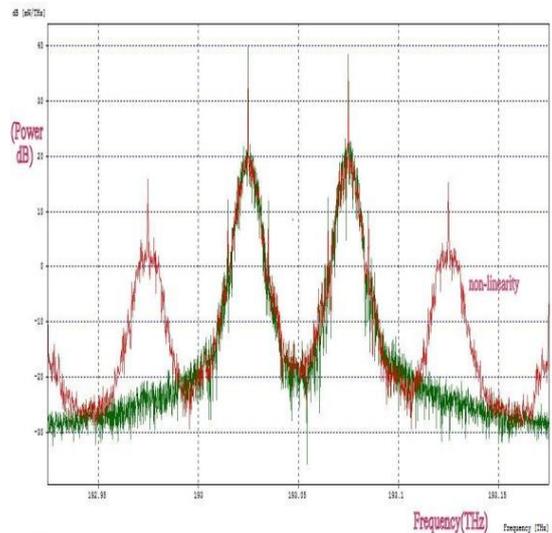


Fig.3(c) Superimposition of Optical Spectrums

Two WDM channels are launched over two DS fiber spans of 150KMeach. The lasers representing the two channels have the same initial polarization (along the x axis), but polarization for one source is rotated around the S2 axis and number of rotation =1 through parametric runs. The FWM products are maximized when the polarizations are aligned and completely reduced to zero when the two polarizations are orthogonal. The results are quoted in Fig.4 (a), Fig.4 (b) and Fig.4 (c). Fig. 4(a) shows optical power spectrum at the fiber input in the range of 192.90THz to 193.20THz and Fig. 4(b) shows the optical power spectrum at the fiber output in the range of 192.90 THz to 193.20THz. the spectrum of the superimposed signal of input optical spectrum and output optical spectrum makes clear that FWM products decrease with increasing polarization in the range of 192.90THz to 193.20THz as shown in Fig.4(c) but these variations are very smaller as compared to that of dispersion.

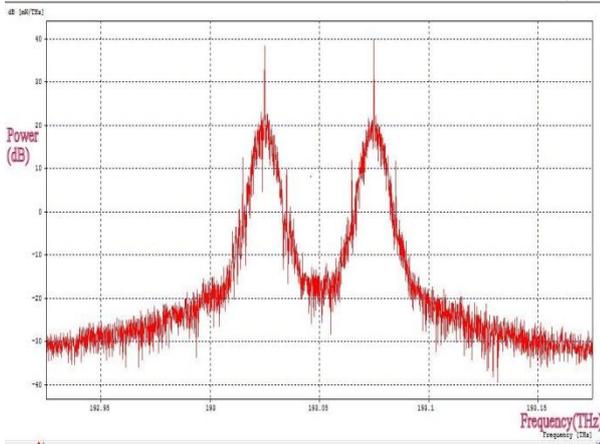


Fig.4 (a) Input Optical Spectrum

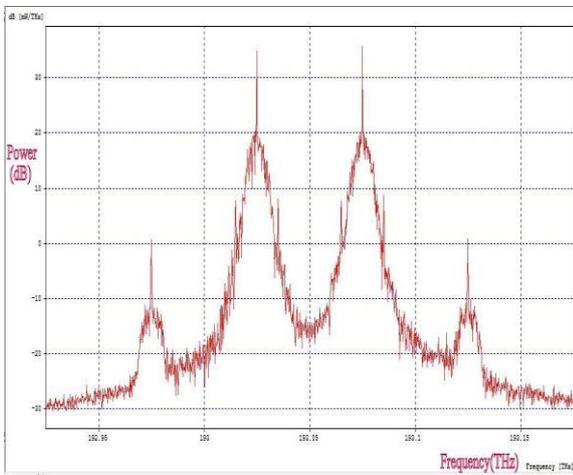


Fig.4 (b) Output Optical Spectrum

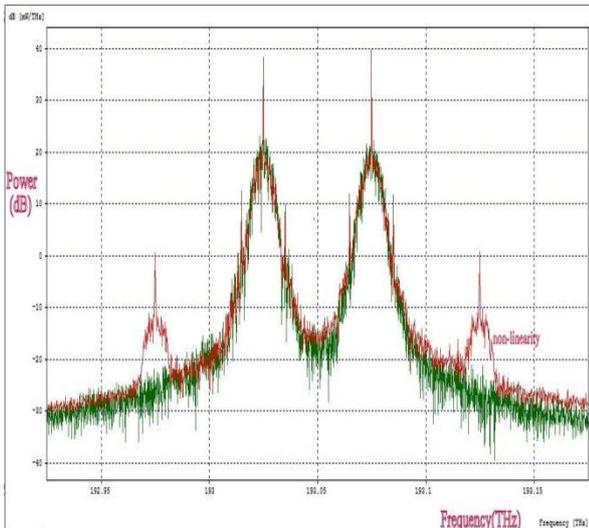


Fig.4(c) Superimposition of Optical Spectrums

IV. SIMULATION OF SPM

A model of WDM optical communication network for dispersion is simulated using OPTSIM to illustrate the non-linear variations in SPM with dispersion and power as shown in Fig.5 and Fig.6.

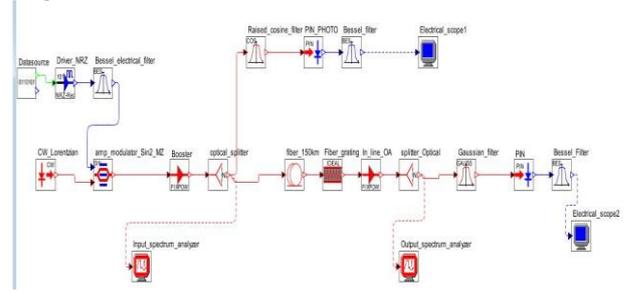


Fig.5. Simulation Diagram for SPM with Dispersion

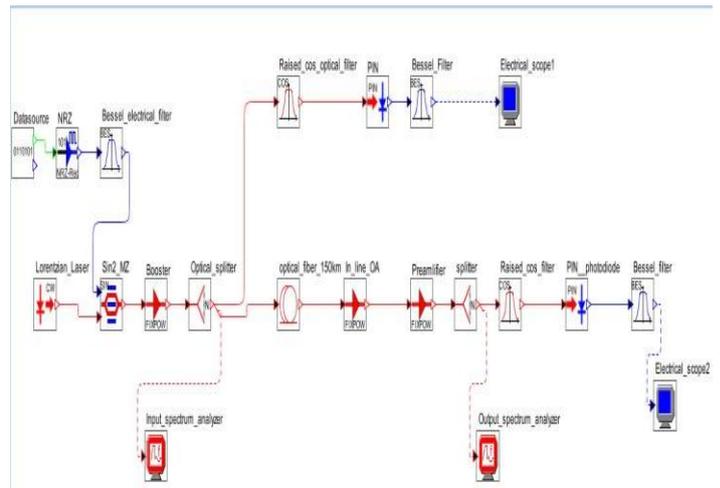


Fig.6 Simulation Diagram for SPM with Power

A 10 Gb/s NRZ signal is sent over optical fiber of 150KM. Dispersion is completely compensated to isolate the SPM phenomenon. The power at the fiber input for each span has been set to 10 dBm. EDFA noise has been turned off. The results are quoted in Fig.7 (a), Fig.7 (b), Fig.(c), Fig.7(d), Fig.7(e). Fig7 (a) shows optical power spectrum at the fiber input in the range of 192.90THz to 193.10THz. Fig.7 (b) shows the optical power spectrum at the output for different setting of dispersion in the range of 192.90THz to 193.10THz. The spectrum of the superimposed signals of input spectrum and output spectrum clears that SPM products decrease with increasing dispersion in the range of 192.90THz to 193.10 THz as shown in Fig.7(c).Fig.7 (d) and Fig.7 (e) depicts eye diagrams. Eye diagram are used in evaluation of performance of wire-line system, we can employ this technique for optical fiber links. The eye-pattern measurements are conducted in time domain and permits the effect of waveform distortion after measurement of BER (Bit Error Rate).The width of eye opening gives a measure of time interval over which the received signal can be sampled without error due to interference from adjacent pulses. The height of eye opening gives measure of idea of noise level. Edge jitter or timing jitter is a signal distortion occurring in optical fiber system due to noise present at the receiver side and pulse distortion introduced in the optical fiber.



Fig.7 (a) Input Optical Spectrum



Fig.7 (b) Output Optical Spectrum

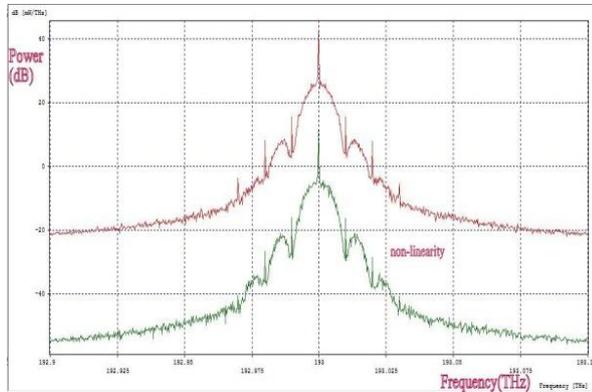


Fig.7(c) Superimposition of Optical Spectrums

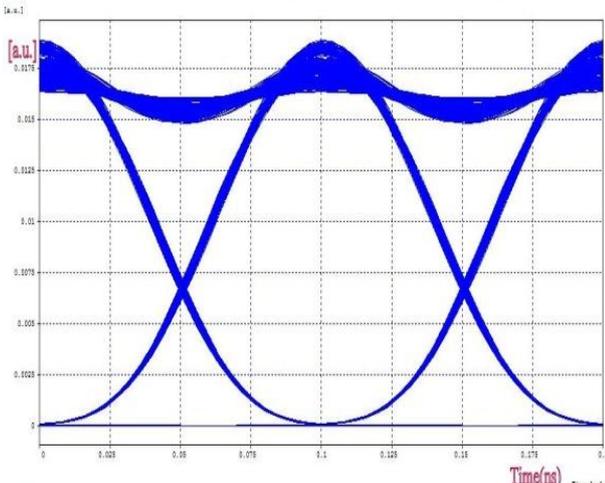


Fig.7 (d) Eye-Diagram on the Output of Raised-Cosine Filter

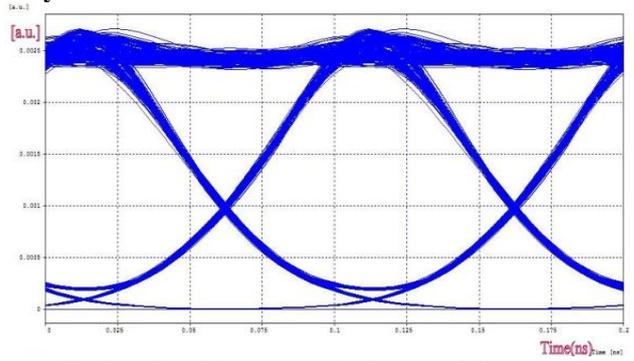


Fig.7 (e) Eye-Diagram on the Output of Gaussian Filter

Fig.7 (d) depicts Eye-Diagram on the output of Raised-Cosine Optical Filter without using the optical fiber cable and hence the following results were observed:

Q Value = 30.15651dB, Bit Error Rate = $1e^{-040}$, Jitter = 0.00303881 ns, Eye opening = 0.0158623au, Average Eye Opening = 0.0168064au and Eye Closure = 0.25198dB.

Fig. 7(e) depicts Eye-Diagram on the output of Gaussian filter by using the optical fiber cable of length 150KM and hence the following results were observed: Q Value = 24.044235dB, Bit Error Rate = $1e^{-040}$, Jitter = 0.0146627 ns, Eye opening = 0.0021097au, Average Eye Opening = 0.00238702 au and Eye Closure = 0.536352dB.

A 10 Gb/s NRZ signal is sent over optical fiber of 150KM. The power at the input to each span is varied from 10 to 17.5 dBm. EDFA noise has been turned off in order to simplify the analysis of SPM. By increasing the power, SPM grows and depletes the signal, and the measured power actually decreases with the increasing of the transmitted power. The eye diagram highlights the PM- AM conversion due to the SPM, the eye opening decreases with increasing transmitted power. The results are quoted in Fig. 8a), Fig.8 (b), Fig.8(c), Fig.8 (d) and Fig.8 (e). Fig.8 (a) shows optical power spectrum at the fiber input in the range of 192.90THz to 193.10THz. Fig.8 (b) shows the optical power spectrum at the output in the range of 192.90THz to 193.10THz. The spectrum of the superimposed signals of input spectrum and output spectrum clears that SPM products decrease with increasing power in the range of 192.90THz to 193.10 THz as shown in Fig.8(c).

Fig.8 (d) depicts Eye-Diagram on the output of Raised-Cosine Optical Filter without using the optical fiber cable and hence the following results were observed:

Q Value = 30.156507dB, Bit Error Rate = $1e^{-040}$, Jitter = 0.00303881 ns, Eye Opening = 0.0158474au, Average Eye Opening = 0.196707au, Eye Closure = 0.251098dB.

Fig.8 (e) depicts Eye-Diagram on the output of Raised-Cosine Optical Filter by using the optical fiber cable of length 150KM and hence the following results were observed: Q Value = 27.064169dB, Bit Error Rate = $1e^{-040}$, Jitter = 0.00256436ns, Eye Opening = 0.0132576 au, Average Opening = 0.0142152au, Eye Closure = 0.302885dB.

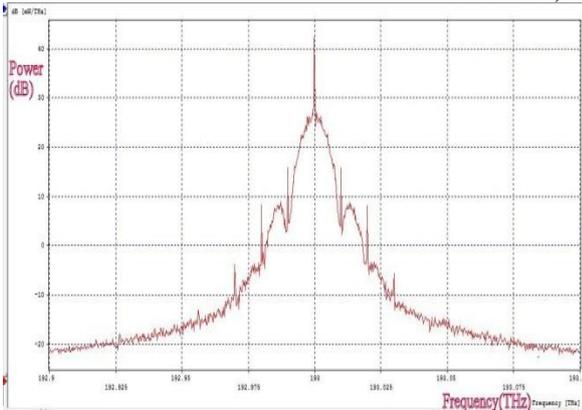


Fig.8 (a) Input Optical Spectrum



Fig.8 (b) Output Optical Spectrum

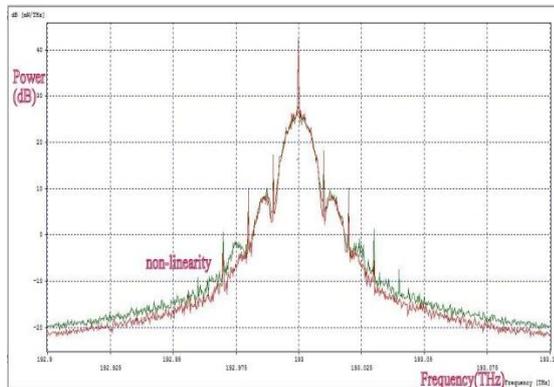


Fig.8(c) Superimposition of Optical Spectrums

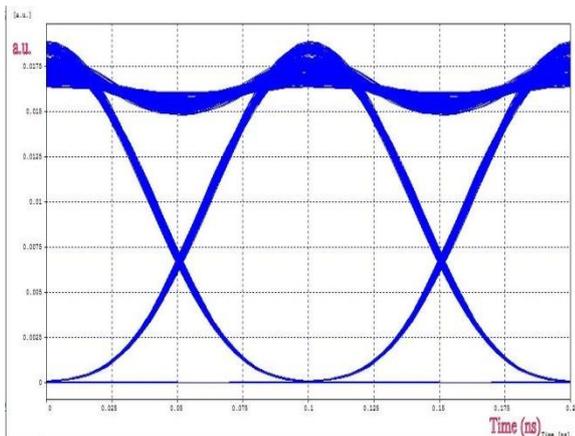


Fig.8 (d) Eye-Diagram on the Output of Raised-Cosine Filter

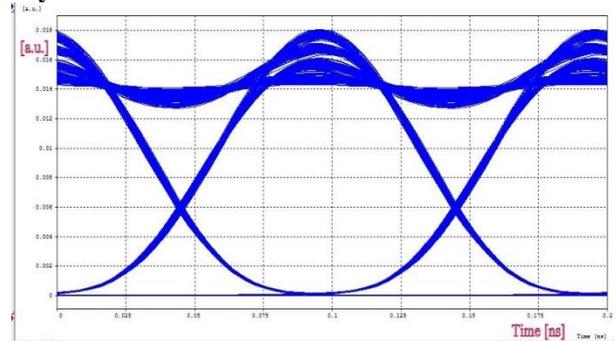


Fig.8 (e) Eye-Diagram on the Output of Raised-Cosine Filter with Optical Fiber

V. SIMULATION OF XPM

A model of WDM optical communication network for dispersion is simulated using OPTSIM to illustrate the non-linear variations in XPM with dispersion as shown in Fig.9.

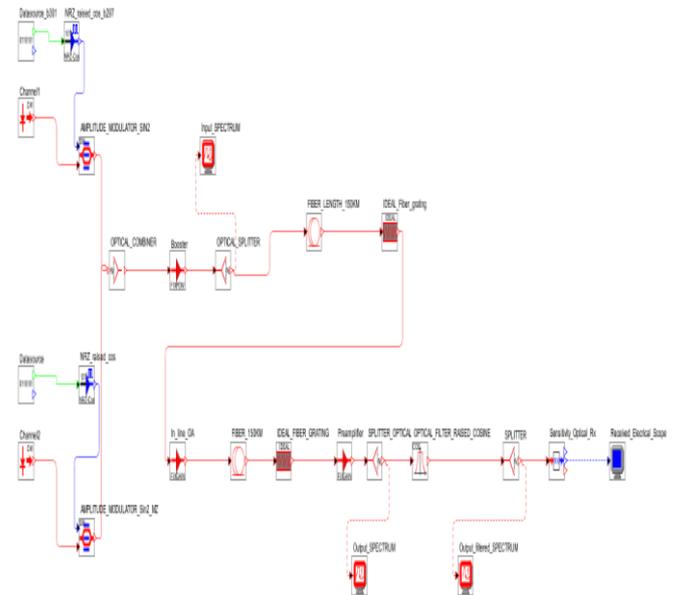


Fig.9. Simulation Diagram for XPM with Dispersion

Two WDM channels are launched over two DS fiber spans of 150 km each. Dispersion is completely compensated at each span to better show the XPM phenomenon. Fig.10 (a) shows optical power spectrum at the fiber input in the range of 192.90THz to 193.20THz. Fig.10(b) shows the optical power spectrum at the fiber output in the range of 192.90 THz to 193.20THz and Fig.10(c) shows the optical filtered output power spectrum in the range of 192.90 THz to 193.20THz. The spectrum of the superimposed signal of input optical spectrum and output optical spectrum makes clear that XPM power decrease with increasing dispersion in the range of 192.90THz to 193.20THz as shown in Fig.10(d). The spectrum of the superimposed signal of input optical spectrum and Filtered output optical spectrum makes clear that XPM power causes a large scale variation with dispersion in the range of 192.90THz to 193.20THz which causes a larger variation as shown in Fig.10(e). Fig.10(f)

shows eye diagram of XPM with dispersion and followings are observed:

Q Value = 8.721812dB, Bit Error Rate = 0.00245937, Jitter = 0.0239933ns, Eye Opening = 0.000121724 a.u., Average Opening = 0.000211421a.u., Eye Closure = 2.397714dB.

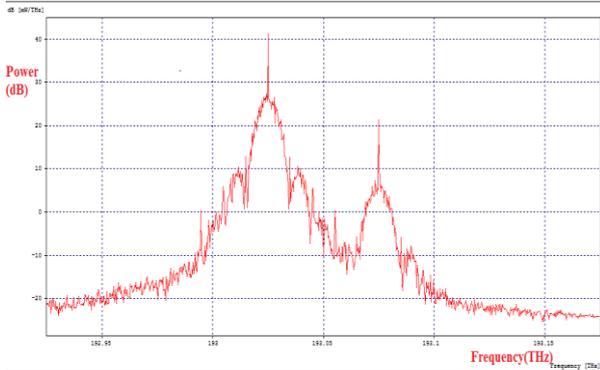


Fig.10 (a) Input Optical Spectrum

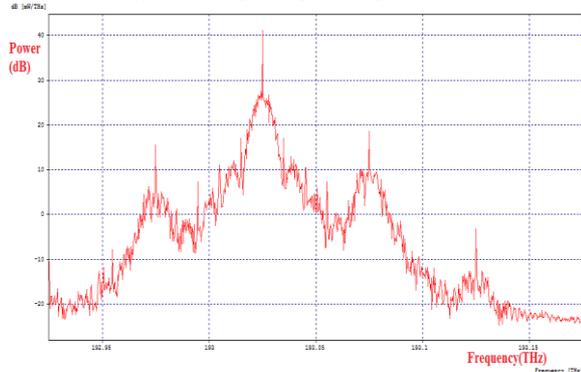


Fig.10 (b) Output Optical Spectrum

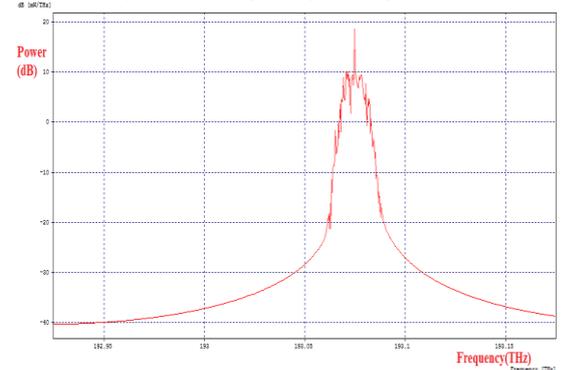


Fig.10(c) Output Filtered Optical Spectrum

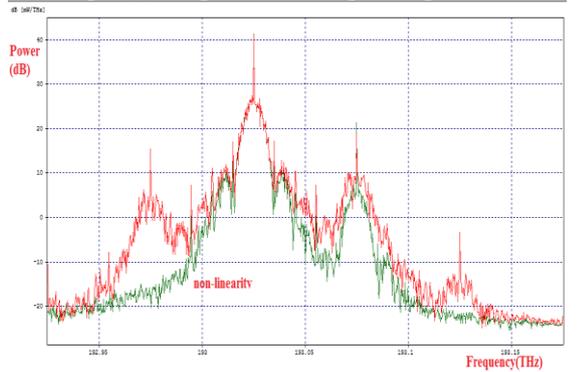


Fig.10 (d) Superimposition of Input & Output Optical Spectrum

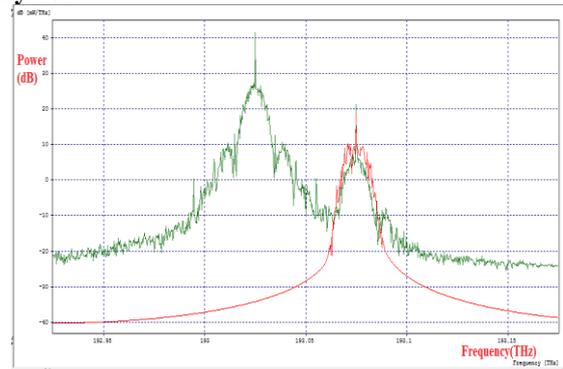


Fig.10 (e) Superimposition of Input & Output Filtered Optical Spectrum

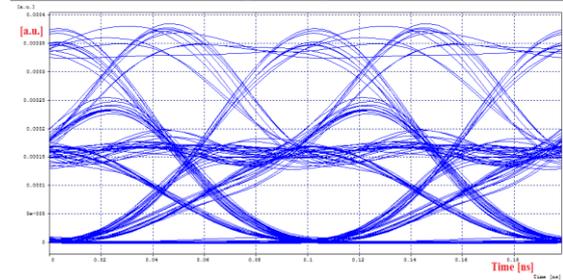


Fig.10 (f) Eye-Diagram

VI. SIMULATION OF SRS

A model of WDM optical communication network for dispersion is simulated using OPTSIM to illustrate the non-linear variations in SRS with ASE as shown in Fig.11.

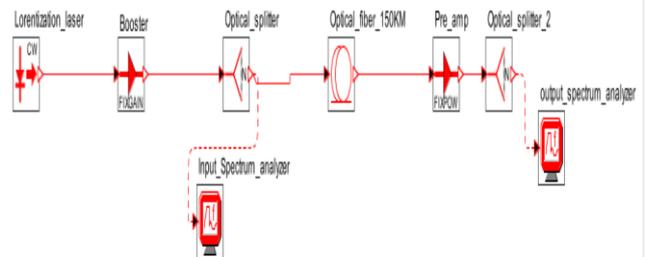


Fig.11 Simulation Diagram for SRS with ASE

A CW signal at 194 THz is amplified by an EDFA to +20 dBm output power and launched onto a fiber. Raman-induced cross-talk in WDM system leads to power re-distribution between higher- and lower-frequency channels. The magnitude of transferred power depends on the channel spacing, signal input power, and Raman gain coefficient. Fig.12(a) shows optical power spectrum at the fiber input in the range of 193.38THz to 193.48THz. Fig.12(b) shows the optical power spectrum at the fiber output in the range of 193.38THz to 193.48THz and Fig.12(c) shows the superimpositions of optical spectrums in the range of 193.38THz to 193.48THz. The spectrum of the superimposed signal of input optical spectrum and output optical spectrum makes clear that SRS product decreases with increasing ASE.

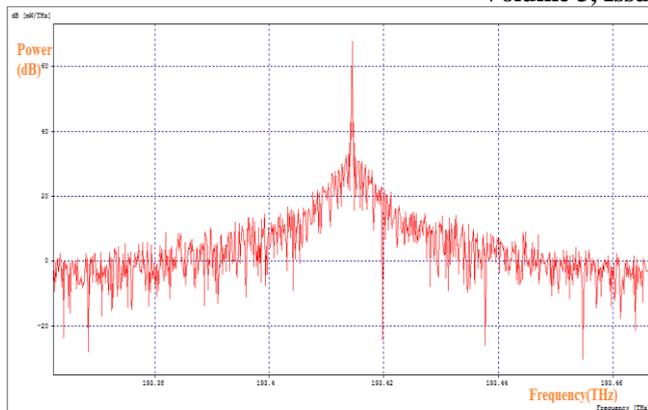


Fig.12 (a) Input Optical Spectrum

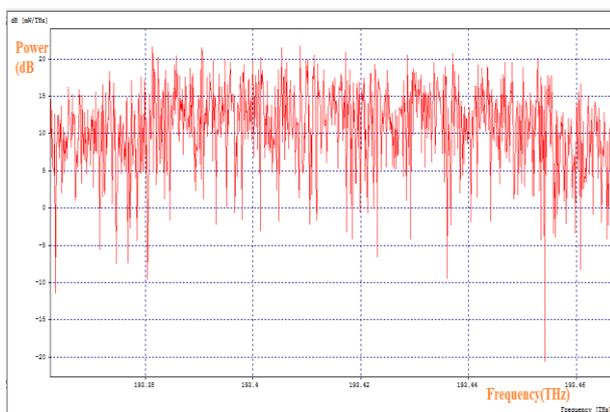


Fig.12 (b) Output Optical Spectrum

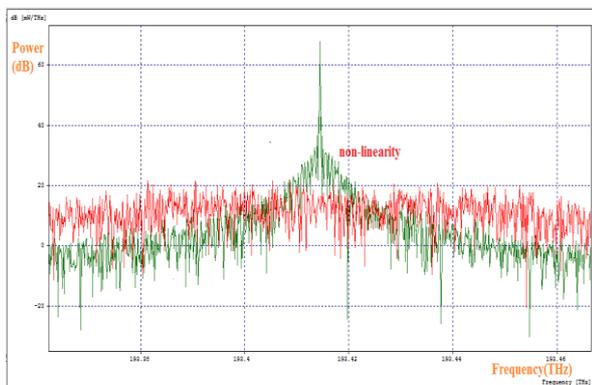


Fig.12(c) Superimposition of Input and Output Optical Spectrum

VII. CONCLUSION

This paper had been simulated on the OPTSIM and gives the variations caused by FWM, SPM, XPM and SRS in WDM optical network network. FWM with dispersion causes larger scale variations in FWM product as compared to FWM with polarization when considering the same parameters. SPM with dispersion causes larger scale variation as the length of the fiber goes on increasing but SPM with power causes smaller scale variations. SPM with power gives Q Value = 27.064169dB, BER = 1e-040, Jitter = 0.00256436ns. SPM with

dispersion gives Q Value = 24.044235dB, BER = 1e-040, Jitter = 0.0146627 ns. XPM with dispersion also causes a larger scale non-linearity in the optical fiber. XPM with dispersion gives Q Value = 8.721812dB, BER = 0.00245937, Jitter = 0.0239933ns. SRS with ASE noise gives a larger scale non-linearity which leads to a greater cross-talk. Hence by using the length of 150km SPM with power causes a very smaller variation.

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