Experimental Analysis and Reduction of FWM Using Optical Rectangle Filter for WDM

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ABSTRACT

Nonlinearities implanted by refractive index and scattering degrade the performance of optical networks. In this paper, FWM (Four Wave Mixing) has been analyzed for four different channels with 10 nm spacing. Due to the presence of resonant frequency, FWM interface of different channels in WDM (Wavelength Division Multiplexing) hinders the performance of the system. The system is affected by nonlinear cross talk. A system with the bandwidth of 10 Gbps has been investigated using External Modulation and an optical rectangle filter as a key parameter to improve the system performance with respect to FWM effect.

Key Words: **Four Wave Mixing, External Modulation, Wavelength Division Multiplexing System, Optical Rectangle Filter.**

1. INTRODUCTION

Nowadays internet services are perforating at access networks; traffic congestion is increasing in core network [1]. In order to meet the requirements optical networks may provide a solution by guaranteeing the delivery of large traffic data in a reliable way [2-3]. For multiple data channels, DWM technique employs wavelength to multiple traffic channels to transmit data for efficient utilization of bandwidth [4-5]. In order to improve the optical communication system fiber nonlinearities and dispersion are the substantial factors that limit the bandwidth of the system [6]. One of the most important nonlinearity categorized in nonlinear refractive index is the FWM.

Factors such as channel power, channel spacing, dispersion effective area and transmission interact distance are the reasons of undesirable frequency harmonics in WDM systems. A number of techniques have been proposed for WDM system to suppress undesirable effects of FWM [7].

Monika, et. al. [6], have worked on different input channels using various parameters for channel spacing on FWM. Experimental results of the proposed work have been analyzed with the help of increasing number of channels to create interference that helps in illustrating FWM effects. The results show FWM is decreases if the number of channels used is less.

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Sharma and Kaur [7] implemented 80 Gbps DWDM system over 100 km to calculate the BER (Bit Error Rate), Q-factor and received power in the presence of FWM under equal and un-equal channel spacing. The result shows the unequal spacing between the channels helps the system perform better. Moreover, Kaur and Singh [8] investigated FWM on 16 channels WDM with different modulation format at different values of dispersion, core effective area and channel spacing in terms of FWM power, BER and Q-factor.

A number of methods has been suggested to minimize the effects of FWM. The FWM has been examined for different values of distance of fiber, modulation formats and channel spacing however, the use of filters for individual channel has rarely been done.

Two most important categories of nonlinearity effects in optical fiber communication are scattering and nonlinear refractive index as shown in Fig. 1 [8].

(i) Nonlinearities that occur as a result of scattering include [8]:

(ii) SRS (Stimulated Raman Scattering)

(iii) SBS (Stimulated Brillouin Scattering)

Nonlinearities that occur due to optical changes in the refractive index are:

(a) SPM (Self-Phase Modulation)

(b) XPM (Cross-Phase Modulation)

(c) FWM (Four Wave Mixing)

1.1 Scattering Nonlinearities

(a) Stimulated Raman Scattering

SRS is the outcome from the interface between the molecular quality of the medium and the incident light [9]. Change in energy is caused by incident photon in this process, either unrestricted or absorbed energy hence stokes and anti-stokes signals are created as shown in Fig. 2 [10].

(b) Stimulated Brillouin Scattering

SBS is categorized as invariant scattering. In this process, changing of the scattered frequency is downward that results in loss of transmitted power in the fiber as sown in Fig. 3 [10]. This effect becomes negligible at low power levels. Threshold transmitted power is established by SBS,

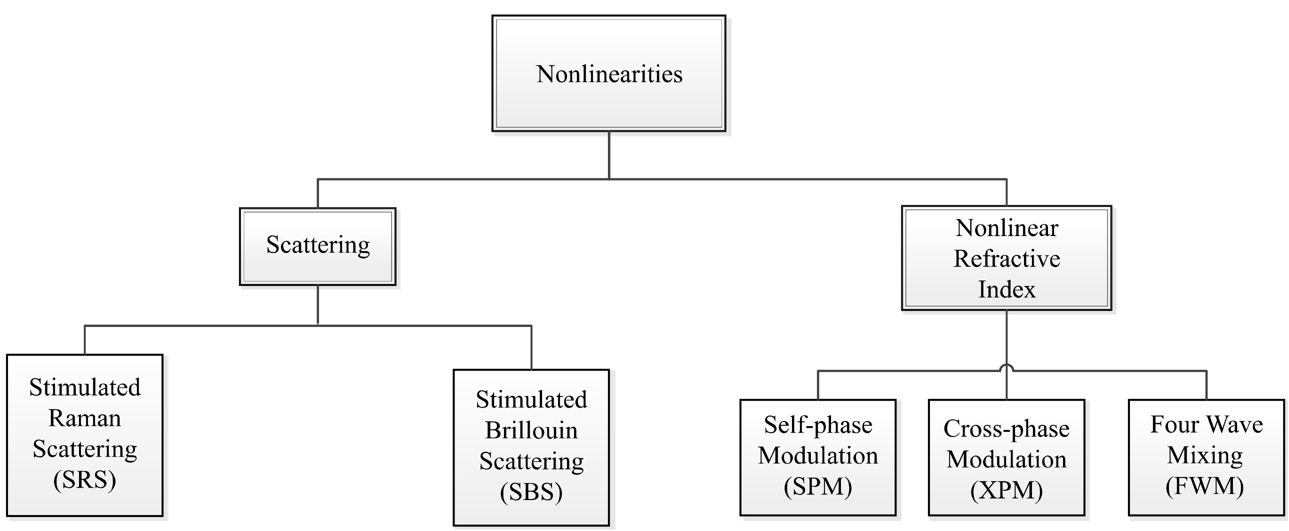

FIG. 1. TYPES OF NONLINEAR EFFECTS

above which significant amount of power is reflected. This reflection makes the light travel in opposite direction and towards the source. Typically, it occurs at the connector interface where refractive index varies. More light is back-scattered since the level would have crossed the SBS threshold as the power level increases. The wavelength and the line width of the transmitter are the parameters used for threshold selection. Lower line width experiences lesser SBS and the decrease in the spectral width of the source reduces SBS [11].

1.2 Refractive Index Nonlinearities

(a) Self-Phase Modulation

In optical fibers, the refractive index has always some dependence on the intensity of an optical signal, which is

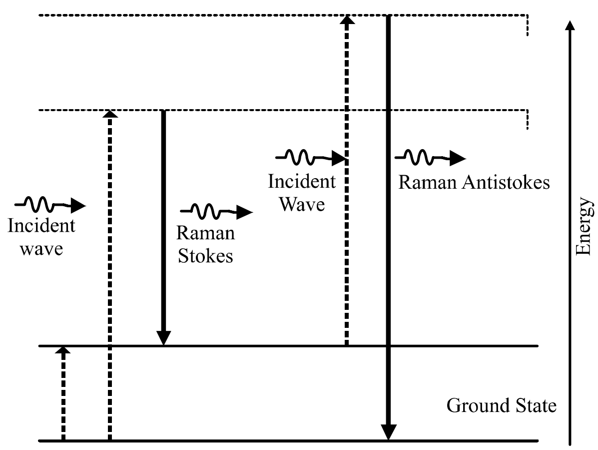

FIG. 2. RAMAN STOKES AND ANTI-STOKES SCATTERING

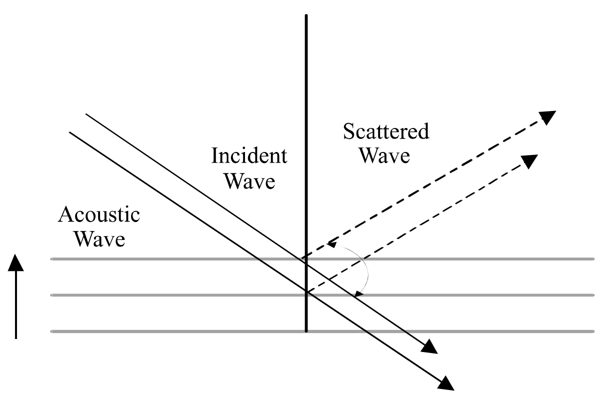

FIG. 3. BRILLOUIN SCATTERING AS A RESULT OF INTERACTION

the optical power per effective area. This relation can be given as:

$$n = n_0 + n_2 I = n_0 + n_2 \frac{P}{A_{eff}} \tag{1}$$

Where n_0 is common refractive index, n_2 is Nonlinear refractive index coefficient, A_{eff} is Effective center area and P is Power of the optical signal.

Within the optical pulse, the pulse moves forward along the optical fiber, this outline also moves along with the pulse. Due to change in the refractive index, there is a phase change within the pulse. The intensity deviation within a pulse in turn causes the phase to vary within the pulse, due to occurrence of Kerr non-linearity within the optical fiber that results SPM; which converts power fluctuations into phase fluctuations in the same wave, since the pulse itself causes the modulation in phase [8].

(b) Cross Phase Modulation

Refractive index depends up on the time varying signal intensity, as shown in Equation (1). It is called XPM. At the same time more optical channels are transmitted in WDM. XPM has more pronounced effect [3].

(c) Four Wave Mixing

The FWM in optical domain is analogous to the inter channel mixing. Two separate frequencies result in the age group of new frequencies, when an amplifier falls in the saturation region [8-10]. Nonlinear performance of an amplifier is due to this FWM. System performance degrades whenever power from one channel leaks into another. Such a power transfer results because of the nonlinear frequency harmonics in optical fibers.

When wavelength of channel spacing is closer to each other in dense wavelength divisions system, FWM occurs. This creates third order undesired harmonics [7].

These interferences with the unique frequency cause the mixing of harmonics, as shown in Fig. 4 [12]. For N input channels there will be M cross products given as:

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

It is possible to solve the arising channels frequencies, if the WDM system is considered as a sum of N monochromatic plane waves. It is possible to solve the arising channels angular frequencies, considering a simple two frequencies f_1 and f_2 if the WDM system is considered as a sum of N mono-chromatic plane waves considering a simple two frequencies system that is experiencing FWM distortion. Four cross products are generated near f_1 and f_2 as shown in Fig. 5.

The three frequencies generate the fourth frequency f_4, due to nonlinearity is given as:

$$f_4 = f_1 \pm f_2 \pm f_3 \quad (3)$$

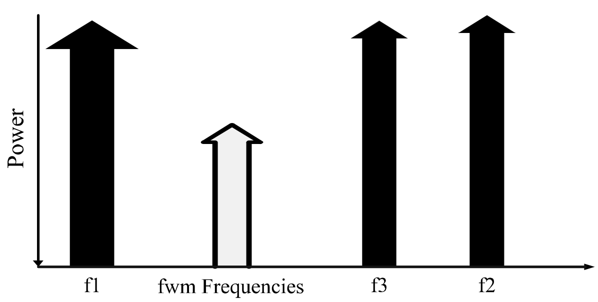

FIG. 4. FOUR WAVE MIXING EFFECT

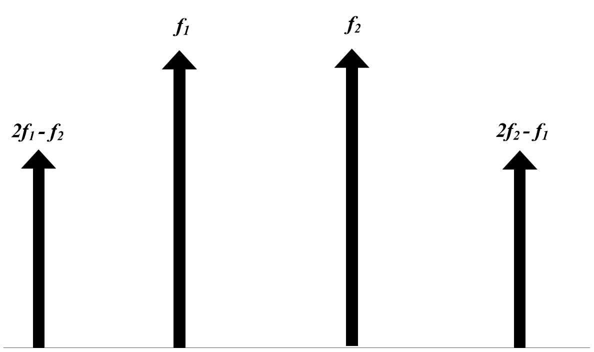

FIG. 5. TWO INPUT SIGNALS ARISING NEW FREQUENCY COMPONENTS DUE TO FWM

Due to the non-linear connections between the three signals, when three distinct frequencies are launched into a non-linear material, new frequencies get generated, in addition to the original frequencies, which are given by Equation (4). Different frequency components lying in the same band as the three original frequencies, can be generated by considering the following possible combinations:

$$(f_1 + f_2 - f_3), (f_1 + f_3 - f_2), (f_3 + f_2 - f_1), (2f_1 - f_2), (2f_1 - f_3), (2f_2 - f_1), (2f_2 - f_3), (2f_3 - f_1), (f_3 - f_2) \quad (4)$$

as the FWM efficiency.

(1) **Channel Spacing**: The mixing efficiency is larger as the channel spacing becomes narrower.

(2) **Fiber Dispersion:** Being strongest at the zero-dispersion point the mixing efficiency is inversely proportional to the fiber dispersion.

1.3 External Modulation

In optical communication system two types of external modulators are mostly used. One of the external modulator is machzhender modulator that works on electro-optic effect. It is an effect in which refractive index changes in the presence of an electric field [10]. Other, external modulator, also known as an electro-absorption modulator, which has been used in our proposed model. This modulator works on franzkeldysh effect in which absorption of a semiconductor material occur when an external electric field is applied [10]. The effective band-gap is decreased when external potential is applied, in other words when E>Eg the light wave will be absorbed. Proper selection of signal wavelength experiences a significant change in absorption when the voltage is applied. It thus becomes possible to achieve proper optical modulation controlled by an electric field [10].

1.4 Optical Rectangle Filter

Rectangle filter is the simplest filter with a linear phase response. It is basically a sinc that eliminates all frequency harmonics above a given cutoff frequency, without affecting lower frequencies.

We discussed basics of nonlinearities in Section 1. Rest of the paper has been organized as follows. Section 2 describes our proposed model. In Section 3, analysis of FWM is presented with respect to graphical representation and effects on Maximum Q-factor, BER and Eye Pattern using optical rectangle filter. Section 4 gives the conclusion of findings.

2. PROPOSED MODEL

Three optical spectrum analyzers have been used to show the frequency components in simulation model's layout. The first optical spectrum analyzer is fixed after WDM multiplexer and second is fixed after the optical amplifier, showing components of FWM and third one is inserted after rectangle optical filter. The generation and degeneration of FWM components are visualized on optical spectrum analyzer.

Two possible solutions to escape FWM are observed, first one is to increase the channel spacing and the second is to use an optical filter. However, channel spacing results change in frequencies which at times may be not required. Hence, the optical rectangle filter may be the best choice to remove the low power frequency components. Optical rectangle filter is basically a since filter that removes all undesired frequency harmonics above a given cutoff frequency without distressing lower frequencies.

Fig. 6 illustrates the WDM system that has been analyzed on optics 7 software. The system has minimum channel spacing of 10 nm and results are reported in the form of Q-factor, minimum BER and Eye Diagram.

In Fig. 7 proposed model (Block Diagram of Fig. 6) of WDM system is designed in which PRBS (Pseudo Random Bit Sequence) generator is recycled whose output is served into a pulse generator to produce NRZ (Non Return to Zero) pulse. The two input contacts are then connected to EAM (Electro Absorption Modulator). One input connection is from continuous wave laser and another is from NRZ pulse generator. A signal is injected in multiplexer and then fed into single mode optical fiber with attenuation of 0.2 db/km. Optical amplifier is used with a gain of 20 dB

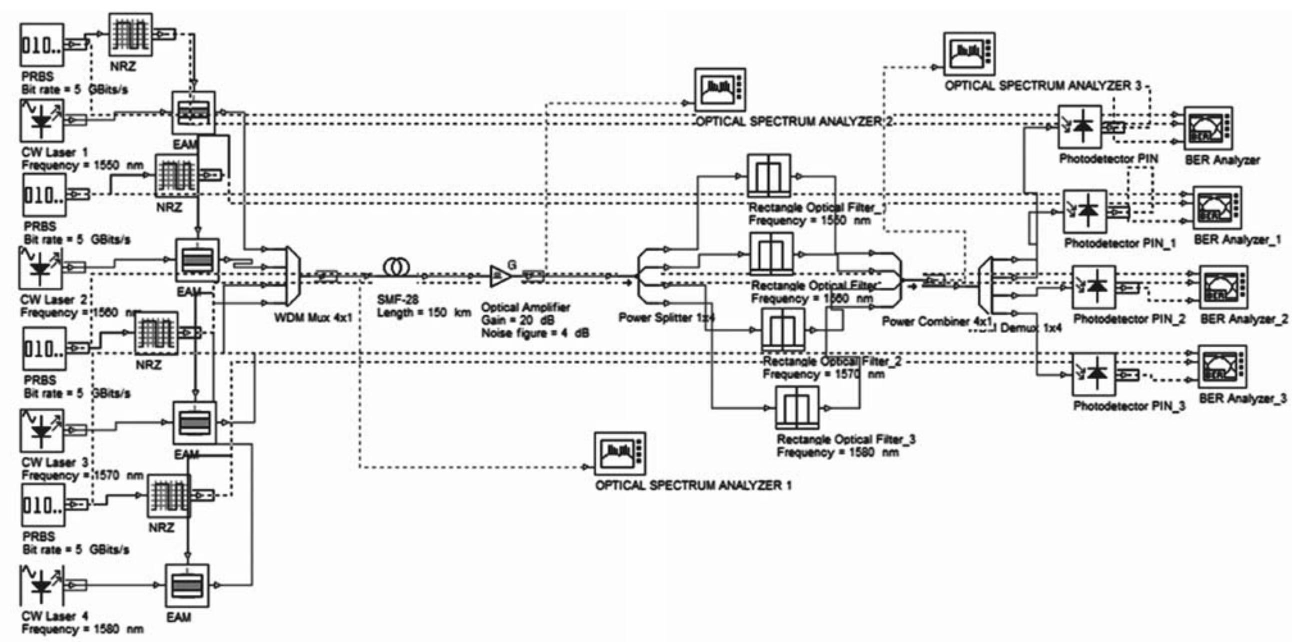

FIG. 6. SIMULATION DIAGRAM OF THE PROPOSRD MODEL

with noise figure value 4 to amplify the signals, however frequency harmonics are also amplified with signals which affect the required signal. To distribute the signals1x4 power splitter is used so that each signal frequency can be filtered out. Optical rectangle filter with the bandwidth of 10 Hz is used to remove the frequency harmonics from desired signals. A 4x1 power combiner is also used to associate the signals. Optical spectrum analyzer analyzes the signals at power combiner. WDM demultilpexer is used at receiver side. PIN photodiode is used to convert optical signals into electrical signals with response of 1 A/W and dark current is 10 nA. BER analyzer is used to check the performance of system in the form of Q-factor, BER and Eye diagram.

3. RESULTS AND DISCUSSION

3.1 Analysis of Four Wave Mixing Nonlinearity

Fig. 8 shows optical spectrum analyzer of the simulation results. It shows how undesired frequency components are generated and removed without increasing the channel spacing.

Above result is reserved at the end of multiplexer using EAM and channel spacing of 10 nm while frequency components are not completely disappeared but at some

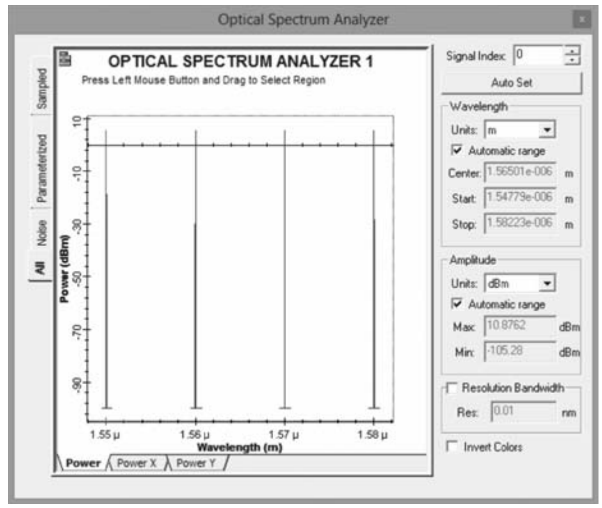

FIG. 8. MODULATED SIGNALS AT WDM

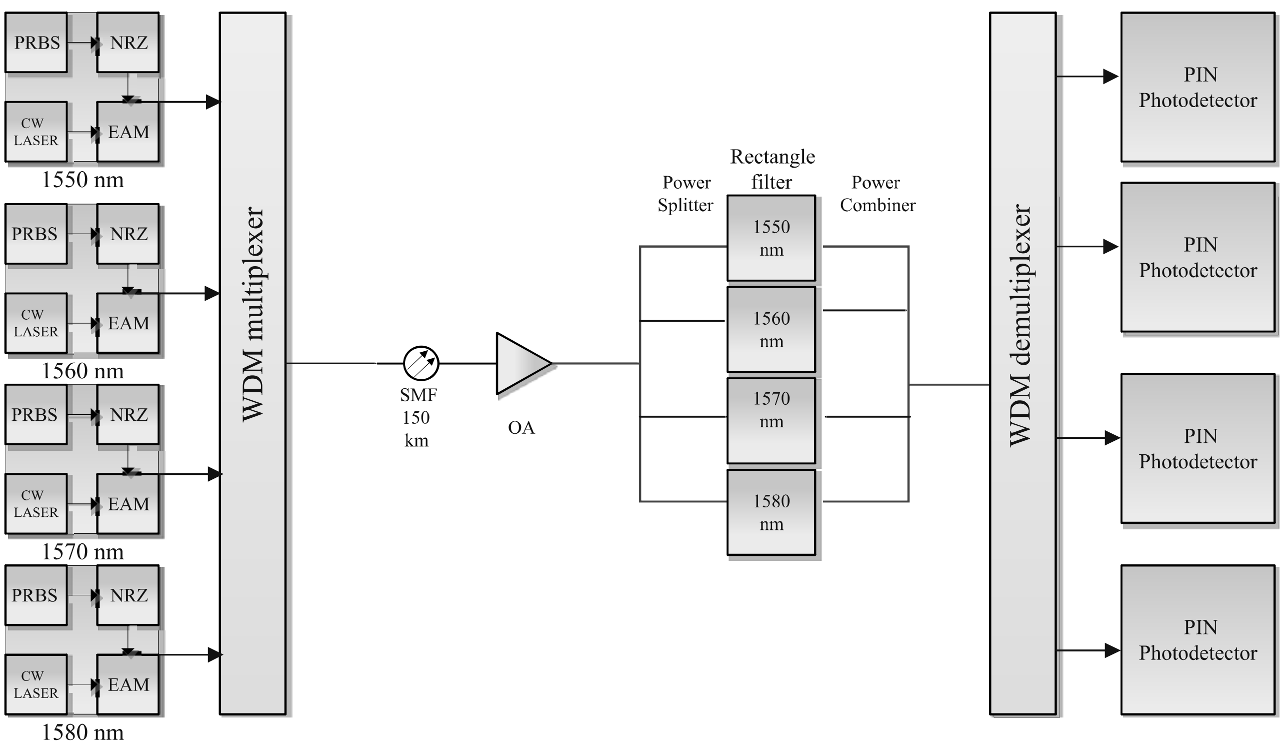

FIG. 7. PROPOSED MODEL OF WDM SYSTEM

wanted level the modules of frequencies are detached and the signal is ready to be transferred on the optical fiber. After signals broadcast on optical fiber with a distance of 150 km, the results are shown in Fig. 9.

The above result has been generated when signal is being transmitted on single mode fiber of 150 km after the optical amplifier with the gain of 20db and noise figure is 4. Due to the non-linear connections between four signals, new frequencies get generated which affect the system performance. In order to avoid FWM nonlinearity, optical rectangle filter is proposed as a possible solution and it gives optimum result. Another advantage of this filter is that it reduces the bulk of amplifiers and signal can transmit at a longer distance. The best results are achieved at 150 km. The results are shown in Fig. 10.

As shown in the Fig.10, the undesired frequency components are removed by optical rectangle filter. The reason behind use of optical filter is its property of linear phase response. In optical, with the rectangle filter lower frequency components are removed at some wanted level which improves the system performance and achieve good Q-factor at receiver side. The output graph of receivers is discussed next with respect to Maximum Q-factor, Minimum BER and Eye diagram.

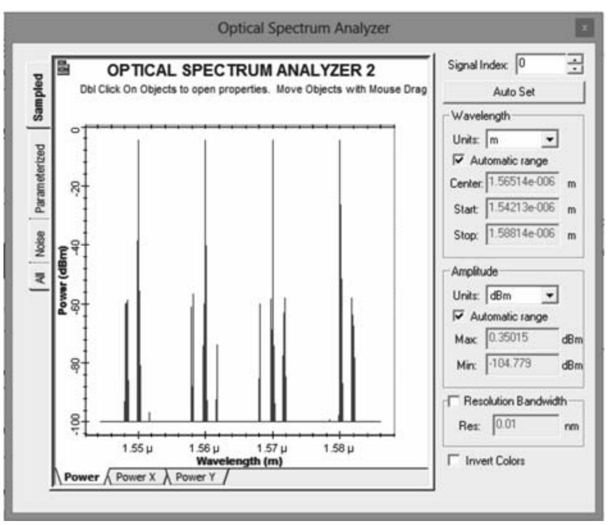

FIG. 9. SIGNALS AFTER TRANSMISSION ON SMF

3.2 Optimized System Performance

Evaluating the optical signal is one of the most important tasks in optical networks [8]. The performance can be measured by Q-factor, BER and Eye pattern. Q-factor is the ratio of difference between the mean value of the signals for 1 and 0 level to the sum of the noise value at those signal level. The formula can be given as:

Quality of the signal in the eye pattern of a digital signal is represented by the Q-factor. The wider the eye the greater is the difference between the values of the 1 level and 0 level which results better BER performance [8].

BER is the rate at which transmitted1 and 0 bits are received in errors is calculated via comparison of transmitted number of bits to the received number of bits. Ideally in optical communication system, it is desired to transmit an optical signal for long length of fiber at high bit rates. Understanding the origin of such errors is essential in order to be able to reduce them and improve the performance of the system. The values of maximum Q-factor and minimum BER of WDM system are listed in Table 1 in order to analyze the system performance after degeneration of FWM components.

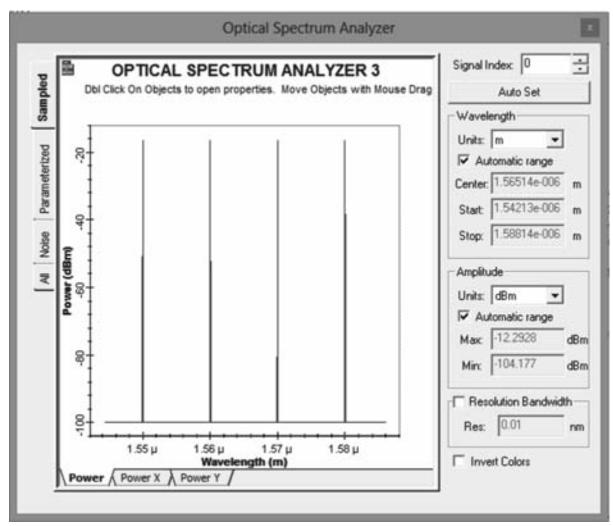

FIG. 10. SIGNALS AFTER OPTICAL RECTANGLE FILTER

The four channels are investigated with channel spacing 10 nm for 10 Gbit/s WDM system. The length of the optical link is 150 km as a Q-factor is increased, BER is reduced, results in an improved WDM system. The output graphs in the form of an Eye Pattern of these values are shown in Figs. 11-14.

As it has already been mentioned eye opening depends on the larger Q-factor. Eye diagrams are a very successful method for the evaluation of the quality of the digital signal. A properly constructed eye should contain all possible bit sequence of simple 101s and 010s. If the eye diagram begins to close to horizontal this is an indication of high waveform timing jitter.

Fig. 11 represents the Q-factor and eye diagram of channel 1 which is 1550 nm. Good Q-factor has been obtained as the result of wider pulses eye diagram that shows the performance of the system is satisfactory. Although in this diagram, the eye is not completely acute but it shows receiver performs well after removal of frequency harmonics. The negligible difference is located at Channel-2, Fig. 12 that is 1560 nm in which Q-factor is slightly different from that of Channel-1, as shown in Table 1. Figs. 13-14 show almost the same Q-factor but slightly higher than Channel-1 and Channel-2. The overall performance of the system is analyzed using the rectangle filter that results in wider eye diagram of the eye and good Q-factor by removing the harmonics of frequencies and improves the WDM system.

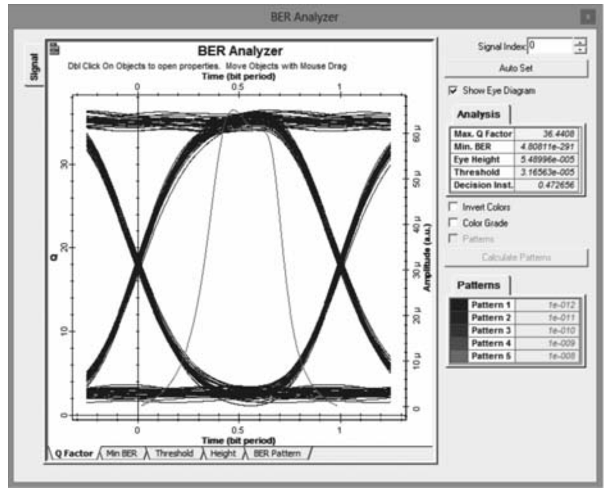

FIG. 11. MAX Q AND EYE PATTERN OF 1550 NM

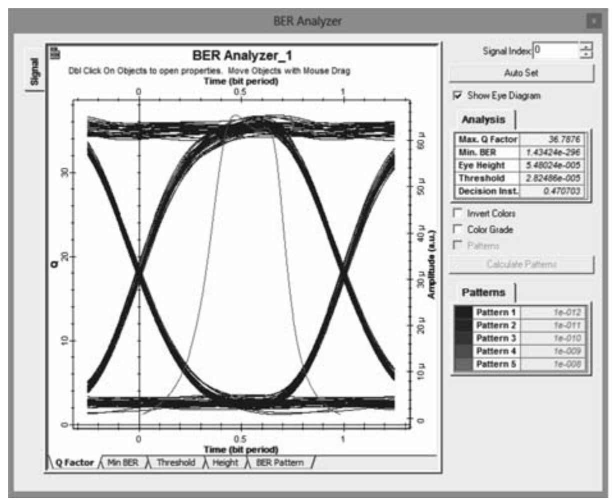

FIG. 12. MAX Q AND EYE PATTERN OF 1560 NM

TABLE 1. VALUES OF MAXIMUM Q FACTOR AND MINIMUM BIT ERROR RATE

No.	Channels (nm)	Maximum Q factor	Minimum Bit Error Rate
1	1550	36.44075104954	4.808114311594e-291
2	1560	36.78755837453	1.434238493947e-296
3	1570	39.47653118995	0
4	1580	39.07318696044	0

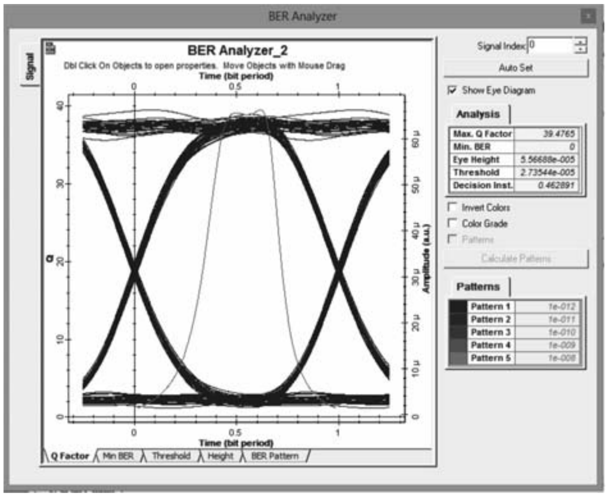

FIG. 13. MAX Q AND EYE PATTERN OF 1570 NM

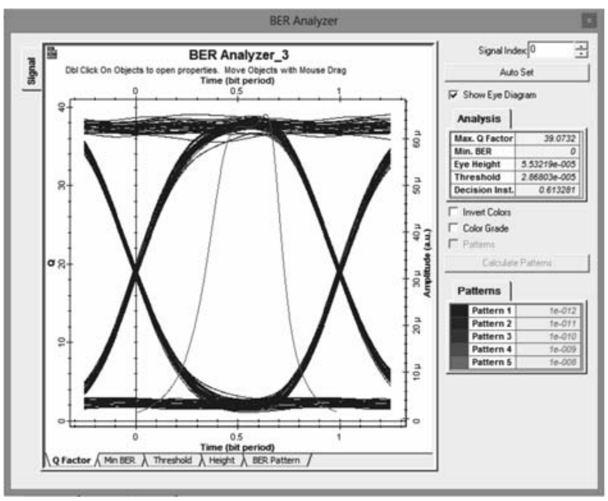

FIG. 14. MAX Q AND EYE PATTERN OF 1580 NM

4. CONCLUSION

From the results obtained, we conclude that, best possible solution for four wave mixing nonlinearity is to use rectangle optical filter that removes the lowest frequency component. It has removed all the harmonics from each frequency, which helps in improving a WDM system of 10 Gbit/s, with a link length of 150 km. To some extent, best possible results have been achieved by the system. The advantage of using the rectangle filter is that there is no need to add a larger space between the channels. It works well at existing frequency channels that may result in achieving good Q-factor and eye broader pulses of WDM system.

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REFERENCES

[1] Karfaa, Y.M., Ismail, M., Abbou, F.M., Shaari, S., and Majumder, S.P., "Effects of Four-Wave Mixing Crosstalk in WDM Networks on the Transmitted Optical Frequencies and Wavelengths of Channels for Various Fiber Types", Proceedings of IEEE Conference on Applied Electromagnetics, pp 1-5, Melaka, 4-6 December, 2007.

[2] Politi, C., Klonidis, D., Mike, J.O., and Mahony, M.J., "Dynamic behavior of Wavelength Converters Based on FWM in SOAs", IEEE Journal of Quantum Electronics, Volume 42, No. 2, pp.108-125, February, 2006.

[3] Keraf, N.D., Kan, P.E., and Blow, K.J., "Performance Comparison of HNLF and DSF Based in Optical Signal Generation", Proceedings of IEEE 2nd International Conference on Photonics, pp.1-4, Kata Kinabalu, 17-19 October, 2011.

[4] Zhang, Q., Zhang, C., Jin, W., and Qiu, K., "Enabled Scalable and Privacy Wavelength Division Multiplexing-Radio Over Fiber System Based on Optical Virtual Private Networks", Optical Engineering, Volume 53, No. 6, June, 2014.

[5] Likai, Z., and Li, G., "Nonlinearity Compensation Using Dispersion-Folded Digital Backward Propagation", Optics Express, Volume 20, No. 13, pp. 14362-14370, 2012.

[6] Monika,W.A., and Kaler, R.S. ,"Investigation of Four Wave Mixing Effect with Different Number of Input Channels at Various Channel Spacing", Optik International Journal for Light and Electron Optics, Volume 124, pp. 4227-4230, 2013.

[7] Sharma, V., and Kaur, R., "Implementation of DWDM System in the Presence of Four Wave Mixing (FWM) under the Impact of Channel Spacing", Optik International Journal for Light and Electron Optics, Volume 124, No. 17, pp. 3112-3114, December, 2012.

[8] Kaur, P., and Singh, K., "Investigations of Four Wave Mixing Effects Using Different Modulation Format in Optical Communication System", International Journal of Engineering Research & Applications, Volume 4, No. 1, pp. 176-181, January, 2014.

[9] Kohl, R., Milovic, D., Zerrad, E., and Biswas, A., "Perturbation of Gaussian Optical Solutions in Dispersion-Managed Fibers", Mathematical and Computer Modelling, Volume 49, Nos. 7-8, pp. 1700-1709, November, 2008.

[10] Khanaa, V., Mohanta, K., and Satheesh, B., "Comparative Study of UWB Communications Over Fiber Using Direct and External Modulations", Indian Journal of Science & Technology, Volume l6, No. 6, pp. 4845-4847, 2013.

[11] Patnaik, B., and Sahu, P.K., "Optimization of Four Wave Mixing Effect in Radio-Over-Fiber for a 32-Channel 40-GBPS DWDM System", International Symposium on Electronic System Design, pp. 119,124, 20-22 December, 2010.

[12] Patel, D.D., and Patel, R.B., "Chromatic Dispersion Compensation for 16x10 Gbps WDM Optical Communication System with Non Linearity", International Journal of Emerging Trends in Electrical & Electronics, Volume l10, No.3, pp. 29-32, 2014.