Hybrid Dispersion Mitigation Techniques in Optical Fiber Communication System

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Abstract- Dispersion is main cause of limit the spectral efficiency and throughput of the optical fiber communication. Chromatic dispersion (CD) is caused by the interaction between the light pulse and the material used to manufacture the optical fiber. Chromatic dispersion is related to linear impairments of optical transmission channel. Dispersion Compensation Fiber (DCF), Fiber Bragg Grating (FBG) and optical phase conjugation (OPC) are techniques to mitigate the CD. In this paper, we are using hybrid compensation model of DCF with OPC and FBG with OPC and observed the effect on Q-factor and Min. BER. Results of Hybrid FBG with OPC are better than DCF with OPC. Back propagation techniques give the joint solution to linear and nonlinear transmission impairments. There are two type of back propagation techniques namely Digital and optical. In optical back propagation (OBP), Optical Phase Conjugation (OPC) followed by Dispersion compensation fiber (DCF) give the compensation to dispersion and nonlinearities present in optical fiber.

keywords- CD, FBG, OPC, DCF.

I. INTRODUCTION

Optical transmission impairments cause severe degradations to the system performance. These impairments are categorized into dispersions and nonlinearities. The dispersion includes the second-order Chromatic dispersion, the third-order dispersion slope, and polarization mode dispersion (PMD). On the other hand, fiber nonlinearities, which are power-dependent impairments, contain a number of effects including intra-channel self-phase modulation (SPM), inter-channel cross-phase modulation (XPM), and four-wave mixing (FWM). Dispersion and nonlinearity impairments are embedded in the nonlinear Schrodinger equation (NLSE) that describes signal propagation along the optical fiber. The most popular method to solve NLSE numerically is the symmetric split-step Fourier method (SSFM). This method, however, encounters a number of issues such as long computation time and artificial errors caused by the windowing effect of fast Fourier transform (FFT) and inverse FFT (IFFT) operations. The symmetric SSFM can overcome some limiting factors of modelling [9].

OPC and DCF was invested to reduce the FWM(four Wave Mixing) in WDM(Wavelength Division Multiplexing) and observed that OSNR (Optical Signal to Noise Ratio) increases with increase in channel spacing in OPC whereas decreases in DCF [2].

Optical signals are attenuated when propagating along the optical fiber link, thus necessitating the signal amplification. This amplification is carried out in the photonic domain by using erbium-doped fiber amplifiers (EDFA). DCFs are normally accompanied by two EDFAs. The first EDFA compensates the attenuation of the preceding SSMF span while the other EDFA boosts optical intensity to a designated level before launching into the next transmission span. From the system point of view, there are two key parameters modelling an EDFA: amplified spontaneous emission (ASE) noise and noise figure (NF).

Evaluation of the performance of the system measure is based on simple metrics such as eye opening (EO) and eye opening penalty (EOP) of detected signals. However, the most popular measure is bit error rate (BER) as a function of the optical signal-to-noise ratio (OSNR), average received powers, or average input powers. Moreover, power or OSNR penalties can be inferred from the obtained BER curves, at a particular BER level.

Chromatic Dispersion (CD) of a single-mode fiber is the expansion of the mode propagation constant or "wave number" parameter β using the Taylor series

$$\beta(\omega) = \frac{\omega n(\omega)}{c} = \beta_0 + \beta_1\Delta\omega + \frac{1}{2}\beta_2\Delta\omega^2 + \frac{1}{6}\beta_3\Delta\omega^3 + \cdots + \frac{1}{n!}\beta_n\Delta\omega^n \quad \text{------(1)}$$

Whereas ω is the angular optical frequency and $n(\omega)$ is the fiber refractive Index.

The parameters β_n represent the nth derivative of β and their meanings are described in the following text.

β_0 involves the phase velocity, v_p, of the optical carrier ω0 and *vp* is defined as¦

$$v_p = \frac{\omega_0}{\beta_0} = \frac{c}{n(\omega_0)} \quad \text{------(2)}$$

ω_0 of the optical carrier frequency indicates the central frequency component of the carrier. Other frequency differences Δω indicate the difference of the sideband component and the central carrier.

• β_1 determines the group velocity v_g that is related to β of the guided mode by

$$v_g = \frac{1}{\beta_1} = \left(\left. \frac{d\beta}{d\omega} \right|_{\omega=\omega_0} \right)^{-1}$$ ------(3)

β_2 is the derivative of the group velocity v_g with respect to frequency, and hence, β_2 clearly shows the frequency dependence of the group velocity. This means that different frequency components of an optical pulse propagate along the optical fiber at different velocities, thus leading to the spreading of the pulse, that is, the dispersion. The parameter β_2 is commonly known as the group velocity dispersion (GVD). The optical fiber exhibits normal dispersions for $\beta_2 > 0$ or anomalous dispersions for $\beta_2 < 0$. A pulse having the spectral width of $\Delta\omega$ and travelling through a length L of fiber is broadened by an amount of time ΔT given by $\Delta T = \beta_2 L \Delta\omega$. In practice, a more common factor to represent the CD of a SMF is the dispersion factor D with the unit of ps/(nm·km). D is closely related to GVD β_2 by

$$D = -\left(\frac{2\pi c}{\lambda^2} \right) \beta_2$$ --------(4)

Where λ is the operating wavelength.
β_3 is the derivative of β_2 and contributes to the dispersion slope $S(\lambda)$ as follows:

$$S = \frac{dD}{d\lambda} = \left(\frac{2\pi c}{\lambda^2} \right) \beta_3 + \left(\frac{4\pi c}{\lambda^3} \right) \beta_2$$ -----(5)

The structure of this paper , section II ,Simulation set-up parameters and layout. Section III, Results and discussions of using different compensation and hybrid techniques (DCF with OPC and FBG with OPC). Section IV is Conclusions and future scope for joint mitigation techniques at receiver and transmitter for linear and nonlinear optical transmission impairments.

Simulation set-up parameters

Category	Parameters	Value
Global Parameters	Bit Rate	10Gb/s
	Sequence length	128 bits
	Sample per bit	64
	No. of samples	8192
Transmitter	Center emission frequency	193.1 THz
	Source line width	10MHz
	Power	5dBm
SMF	Span length	5 to 100Km (varies)
	Dispersion	16 ps/nm-km
	Dispersion slope	0.08 ps/nm^2-km
	Attenuation	0.2 dB/Km
	Non linear index	2.6x10^{-20} m^2/W
	Core area	80 u m^2
	PMD link design	0.2 ps/(Km)$^{0.5}$
DCF	Span length	20 Km
	Dispersion	-80 ps/nm-km
	Dispersion slope	0.21 ps/nm^2-km
	Attenuation	0.6 dB/Km
	Non linear index	3.0x10^{-20} m^2/W
	Core area	30 u m^2
	PMD link design	0.2 ps/(Km)$^{0.5}$
EDFA	Noise figure	4 dB
	Gain	20dB (varies)
FBG	Frequency	193.1 THz
	Length	1 to 7 mm
MZIM MODULATOR	Extinction Ratio	30
	Bias Voltage	4V

Experimental set-up

Case1. Experimental set-up is for dispersion map at different fiber length 5Km to 100 Kms.

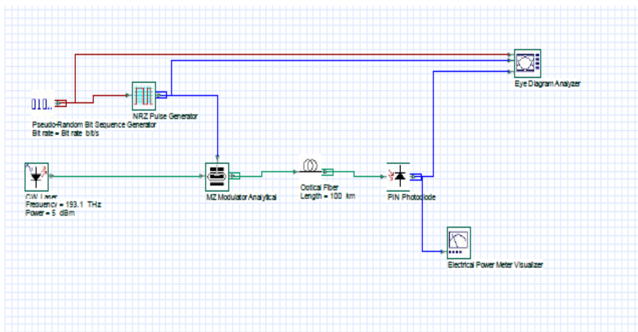

Fig. 1. Optical Transmission system (at different fiber length)

In Fig. 1, optical transmission layout simulated with variation in optical fiber length and observed the effect of change in length of optical fiber from 5 Km to 100 Km on performance metrics like Q-factor, BER and Eye opening etc (see Table 1).

Table 1: Observation at Receiver (change in length of optical fiber from 5 Km to 100 Km)

Fiber length(Km)	5	10	20	30	50	70	100
Max. Q Factor	27.6 655	14.064 4	9.6250 5	7.9031 6	3.3171 8	3.185 43	0
Min. BER	7.00 252e -169	3.0898 9e-045	3.0706 1e-022	1.0982 9e-015	0.0003 79999	0.000 69972	1
Eye Height	0.00 2261 11	0.0016 6966	0.0009 24624	0.0005 53389	3.3432 6e-005	6.730 63e-006	0
Thresh old	0.00 0411 902	0.0008 62011	0.0005 31147	0.0001 92295	0.0001 07107	5.645 51e-005	0
Decisio n Inst.	0.31 25	0.2343 75	0.2968 75	0.4062 5	0.4531 25	0.578 125	0
Total power(d Bm)	25.0 63	27.067	31.079	34.970	43.030	51.20 1	62.70 7

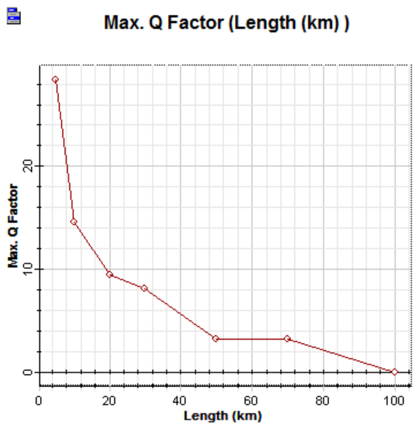

Fig.2 : Q-factor Vs Length of Optical Fiber

In fig. 2 Q-factor decreases with increase in length of optical fiber.

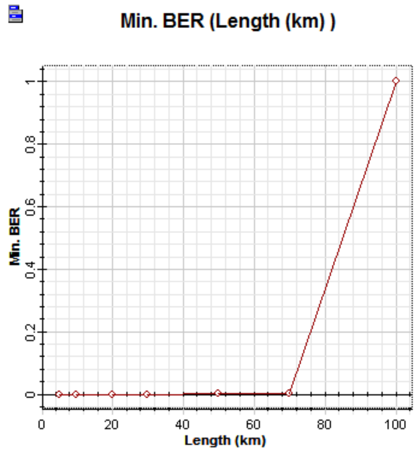

Fig. 3: Min. BER Vs Length of Optical Fiber

Case 2. Fiber Bragg Grating (FBG)

Experimental set-up is for dispersion map using FBG at different fiber length 5Km to 100 Kms.

A fiber Bragg grating acts as an optical filter because of the existence of a stop band, the frequency region in which most of the incident light is reflected back. The stop band is centered at the Bragg wavelength $\lambda_B = 2n\Lambda$, where Λ is the grating period and n is the average mode index. The periodic nature of index variations couples the forward- and backward-propagating waves at wavelengths close to the Bragg wavelength and, as a result, provides frequency-dependent reflectivity to the incident signal over a bandwidth determined by the grating strength. In essence, a fiber grating acts as a reflection filter.

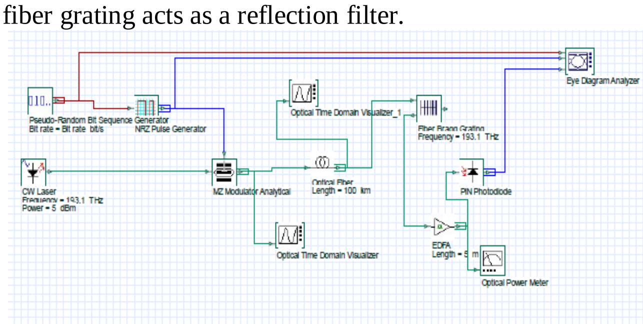

Fig. 4: Optical Transmission system using FBG

In Fig. 4, optical transmission layout simulated with inline FBG to compensate the dispersion and observed the effect of change in length of optical fiber from 5 Km to 100 Km on performance metrics like Q-factor, BER and Eye opening etc (see Table 2).

Table 2: Observation at Receiver (change in length of optical fiber from 5 Km to 100 Km)

Fiber length (Km)	5	10	20	30	50	70	100
Max. Q Factor	64.35 18	55.57 82	31.33 72	15.72 16	8.553 22	7.261 32	3.7334
Min. BER	0	0	6.719 54e-216	4.024 27e-056	5.553 58e-018	1.909 58e-013	9.36429 e-005
Eye Height	0.101 961	0.118 454	0.115 84	0.096 5574	0.075 0921	0.050 8039	0.00760 259
Thresh old	0.002 8576 9	0.010 8423	0.047 6472	0.018 6746	0.042 0819	0.048 6343	0.02359 4
Decisio n Inst.	0.687 5	0.687 5	0.328 125	0.718 75	0.593 75	0.531 25	0.48437 5
Total power (dBm)	- 17.52 7	- 17.48 9	- 17.40 4	- 17.29 3	- 16.98 4	- 16.42 0	14.458

<u>Comparisons of Q-Factor w.r.t. Length of Fiber Case</u>

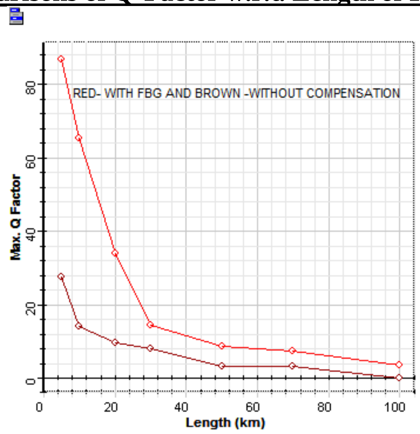

Fig. 5: Q-factor Vs Length of Optical Fiber (with FBG and without compensation)
(Case 1—Brown and Case 2- Red)

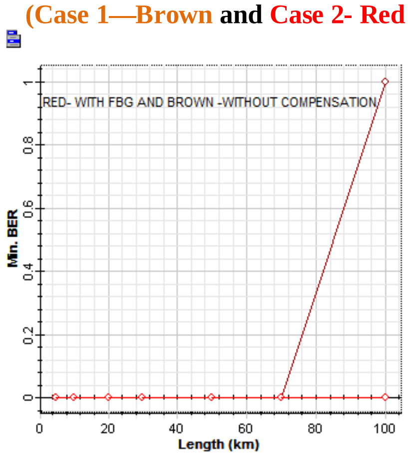

Fig. 6: Min. BER Vs Length of Optical Fiber (with FBG and without compensation)

<u>FBG (Length varies from 1mm to 7mm)</u>

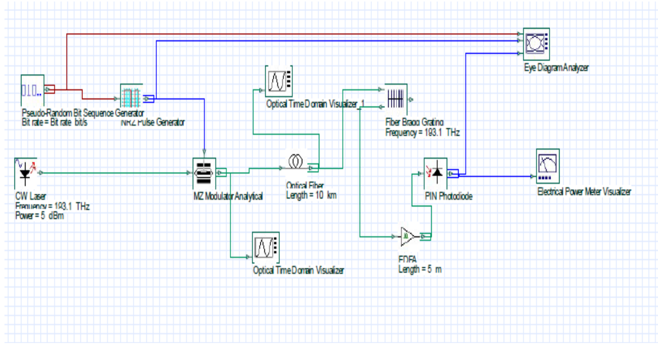

Fig. 7: Optical Transmission system using different length of FBG

Fig. 7, this simulation layout is simulated with change in length of FBG and observed the effect on Q-factor, Min. BER and Total Power at output.

Table 3: Observation at Receiver (change in length of FBG from 1mm to 7mm)

FBG length(mm)	1	2	5	7
Max. Q Factor	12.946 7	33.3492	42.8405	53.9768
Min. BER	8.1182 1e-039	2.3558e-244	0	0
Eye Height	0.0642 037	0.0935933	0.107937	0.111822
Threshold	0.0073 2828	0.0064351 6	0.026285 7	0.012280 1
Decision Inst.	0.4375	0.4375	0.265625	0.703125
Total power (dBm)	-4.995	-7.025	-7.751	-7.947

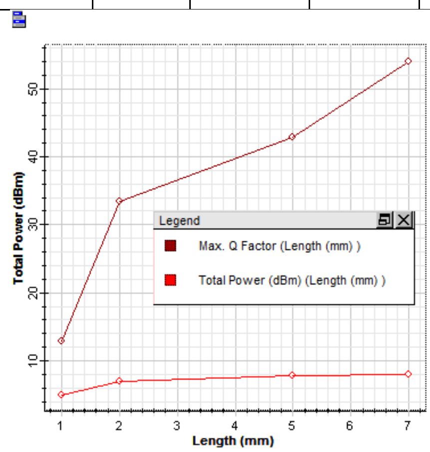

Fig. 8: Output Power and Q- Factor Vs Length of FBG

From Fig. 8, both output power and Q-factor increases with change in length of FBG.

Case 3. Dispersion-compensating fiber (DCF)

Dispersion-compensating fiber (DCF) provides an all-optical technique that is capable of compensating the fiber GVD completely if the average optical power is kept low enough that the nonlinear effects inside optical fibers are negligible. It takes advantage of the linear nature of Optical fiber.

Pre- compensation DCF

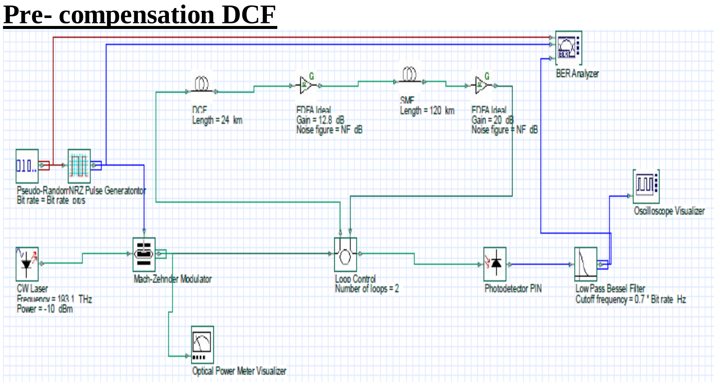

Fig. 9: Pre- compensation DCF

Post- compensation DCF

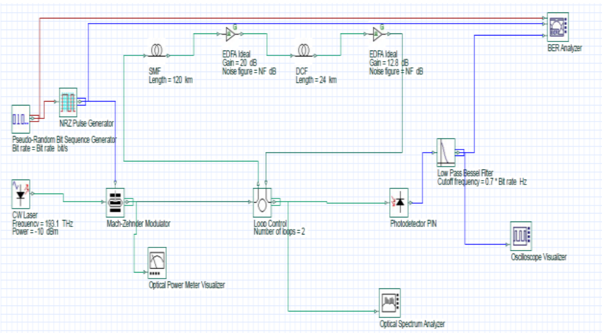

Fig. 10: Post- compensation DCF

Symmetrical DCF Compensation

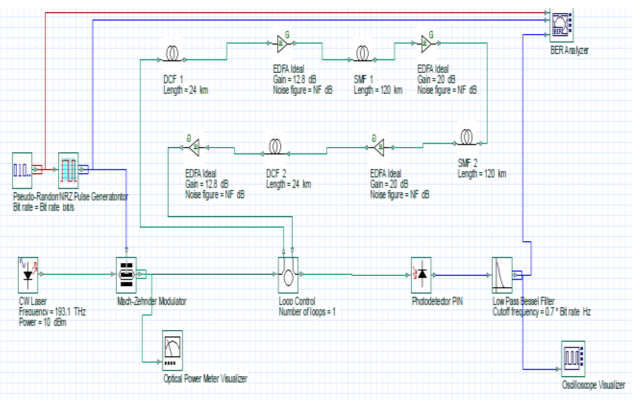

Fig. 11: Symmetrical DCF Compensation

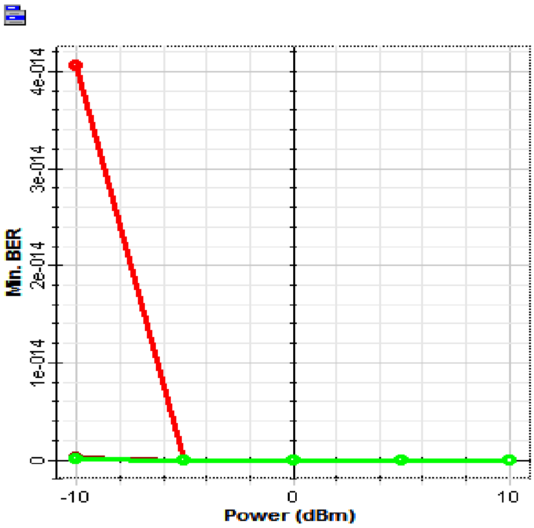

Fig. 12: Comparison Min. BER Vs Input Power of Pre, Post and Symmetrical DCF

(Symmetrical -Brown, Pre- Red and Post- Green)

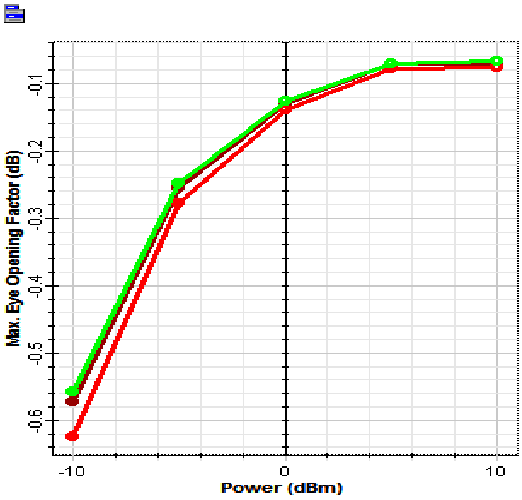

Fig. 13: Comparison Max. Eye Opening Vs Input Power of Pre, Post and Symmetrical DCF

(Symmetrical -Brown, Pre- Red and Post- Green)

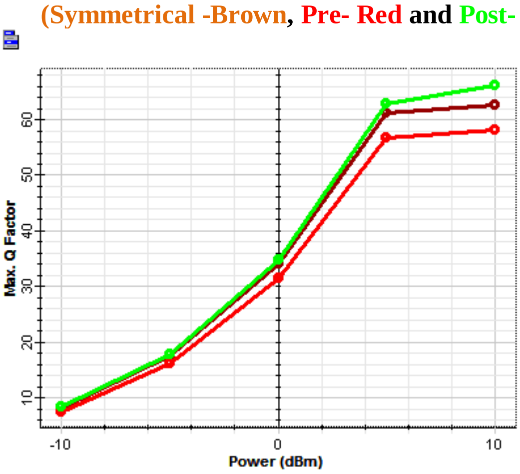

Fig. 14: Comparison Q-Factor Vs Input Power of Pre, Post and Symmetrical DCF

(Symmetrical -Brown, Pre- Red and Post- Green)

On the comparison of all of three, minimum BER is maintained in case of Post compensation DCF with increase in input power. Value of Q- factor increases with increase input power level.

Case 4- Optical Phase Conjugation (OPC)

The use of optical phase conjugation (OPC) for dispersion compensation was proposed in 1979, it was only in 1993 that the OPC technique was implemented experimentally and attracted considerable attention. The OPC is a nonlinear optical technique.

A dispersion-management scheme is quite simple and can be understood by using the pulse-propagation equation and written as

$$\frac{\partial A}{\partial z}+\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3}=0 \quad \text{--------(6)}$$

where A is the pulse-envelope amplitude. The effects of third-order dispersion are included by the β_3 term. In practice, this term can be neglected when β_2 exceeds 0.1 ps^2/km.

OPC can compensate the GVD is to take the complex conjugate of above equation

$$\frac{\partial A^*}{\partial z}-\frac{i\beta_2}{2}\frac{\partial^2 A^*}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A^*}{\partial t^3}=0 \quad \text{------(7)}$$

The phase-conjugated field A^* propagates with the sign reversed for the GVD parameter β_2. If the optical field is phase-conjugated in the middle of the fiber link, the dispersion acquired over the first half will be exactly compensated in the second-half section of the link. Since the β_3 term does not change sign on phase conjugation, OPC cannot compensate for the third-order dispersion. In fact, it is easy to show, by keeping the higher-order terms in the Taylor expansion, that OPC compensates for all even-order dispersion terms while leaving the odd-order terms unaffected. The effectiveness of mid-span OPC for dispersion compensation can also be verified. The optical field just before OPC is obtained by using z = L/2 in this equation. The propagation of the phase-conjugated field A* in the second-half section then yields

$$A^*(L,t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{A}^*\left(\frac{L}{2},\omega\right)\exp\left(\frac{i}{4}\beta_2 L\omega^2-i\omega t\right)d\omega \quad \text{---(8)}$$

where $\tilde{A}^*(L/2,\omega)$ is the Fourier transform of A* (L/2, t) and is given by

$$\tilde{A}^*(L/2,\omega)=\tilde{A}^*(0,-\omega)\exp(-i\omega^2\beta_2 L/4) \quad \text{---(9)}$$

Thus, except for a phase reversal induced by the OPC, the input field is completely recovered, and the pulse shape is restored to its input form. Since the signal spectrum after OPC becomes the mirror image of the input spectrum, the OPC technique is also referred to as mid-span spectral inversion.

OPC

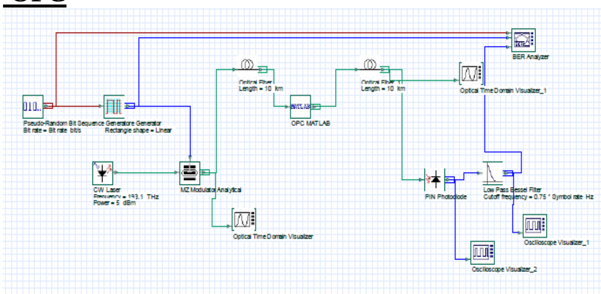

Fig. 15: Optical Phase conjugation(OPC) compensation

Results observed on simulation with OPC compensation with different length (both equal half length) optical fiber with 10Gb/s.

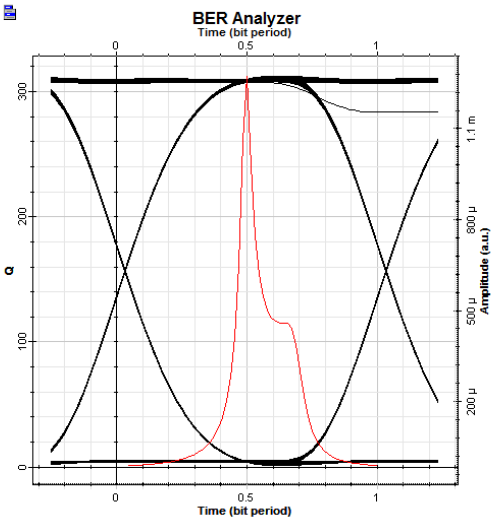

Fig. 16: Eye Diagram and Q-factor

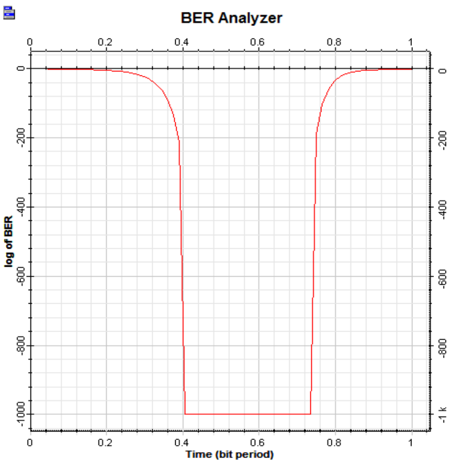

Fig. 17: Min. BER

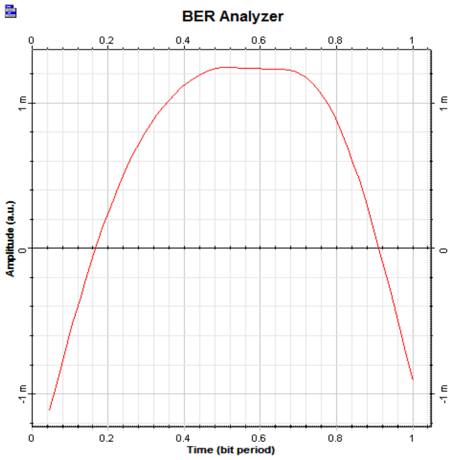

Fig. 18: Eye Opening Height

Table 4: Observation at Receiver (change in length of Optical fiber (from 10Km to 70Km)

Length of Optical fiber (Km)	10	20	30	50	70
Max. Q Factor	317.371	145.085	73.6949	11.4694	0
Min. BER	0	0	0	9.33954e-031	1
Eye Height	0.00124555	0.000489793	0.000190621	2.31136e-005	0
Threshold	0.000120671	6.01427e-005	5.03527e-005	1.39554e-005	0
Decision Inst.	0.53125	0.53125	0.53125	0.453125	0
Output power (dBm)	-31.468	-39.470	-47.474	-63.463	-78.858

From table 4, Decreases the Q –factor as Increases the equal half length of optical fiber

Hybrid DCF with OPC

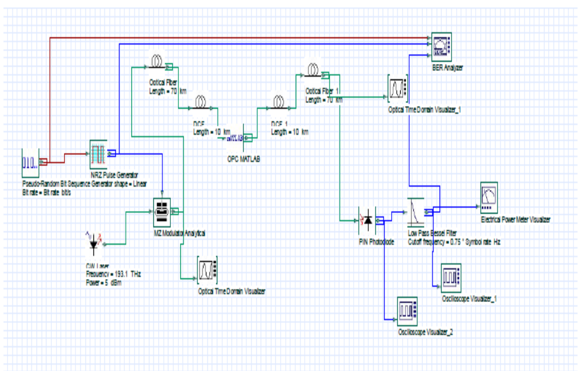

Fig. 19: Hybrid of DCF and Optical Phase conjugation(OPC) compensation

Table 5: Observation at Receiver (change in length of Optical fiber (from 10Km to 70Km)

Length of Optical fiber (Km)	10	20	30
Max. Q Factor	31.4885	12.7099	5.1178
Min. BER	6.2169e-218	2.5953e-037	1.54398e-007
Eye Height	7.21544e-005	2.39877e-005	5.18165e-006
Threshold	3.6729e-005	1.45963e-005	6.46966e-006
Decision Inst.	0.484375	0.453125	0.421875
Output power (dBm)	-55.463	-63.456	-71.306

Hybrid FBG with OPC

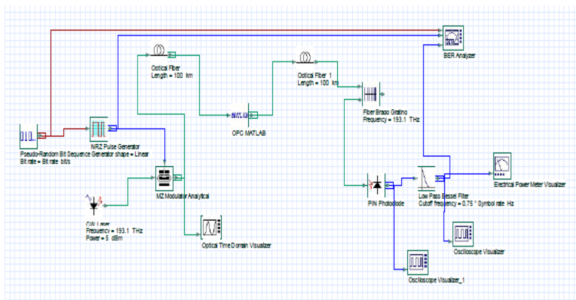

Fig. 20: Hybrid of FBG (Length =7mm) and Optical Phase conjugation(OPC) compensation

Table 6: Observation at Receiver (change in length of Optical fiber (from 10Km to 50Km)

Length of Optical fiber (Km)	10	20	30	50
Max. Q Factor	72.6303	58.4852	39.8396	11.8617
Min. BER	0	0	0	9.35025e-033
Eye Height	0.000942963	0.000373217	0.000145108	1.8961e-005
Threshold	0.00052948	0.000219323	8.09119e-005	1.21143e-005
Decision Inst.	0.390625	0.390625	0.421875	0.4375
Output power (dBm)	-41.801	-49.734	-65.723	-80.838

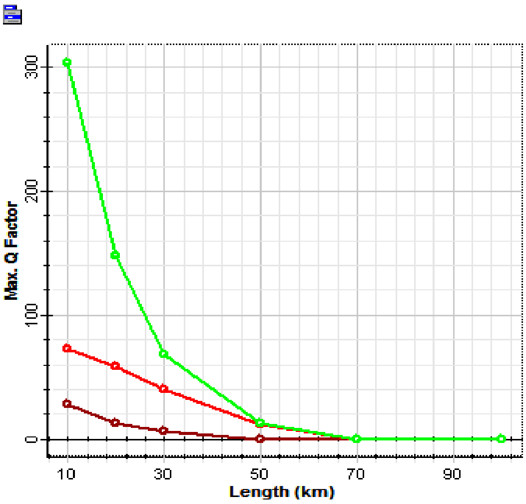

Fig 21: Q-Factor varies with Length of SMF (Brown-DCF with OPC, Red-FBG with OPC and Green-OPC)

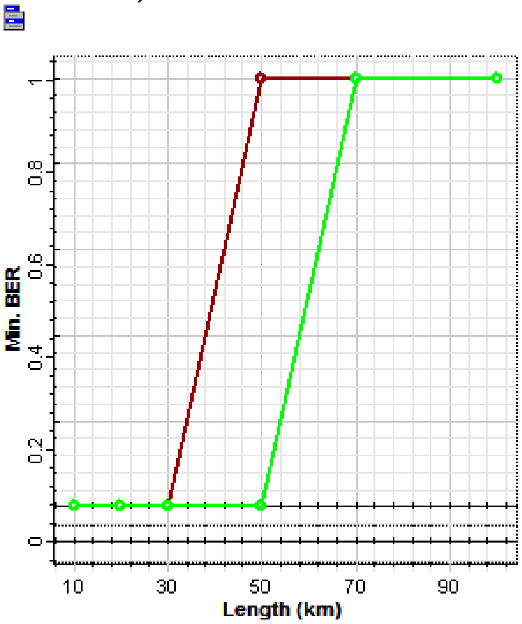

Fig 22: Min. BER varies with Length of SMF (Brown-DCF with OPC, Red-FBG with OPC and Green-OPC)

II. RESULTS AND CONCLUSIONS

Cases	Q-factor	Min. BER	Output Power
Fiber Length increases (with compensated)	↓	↑	↑
Fiber Length increases (with FBG)	↓	↑	↓
Length of FBG increases	↑	↓	↑
Input Power increases(Pre- DCF compensation)	↑	↓	↑
Input Power increases(Post- DCF compensation)	↑	↓	↑
Input Power increases(Symetrical-DCF compensation)	↑	↓	↑
Fiber Length increases (with OPC)	↓	↑	↑
Fiber Length increases (Hybrid DCF with OPC)	↓	↑	↑
Fiber Length increases (hybrid FBG with OPC)	↓	↑	↑

We have observed that increases in input power level and length of optical fiber increase in BER decrease in Q-factor by using different dispersion In-line mitigation techniques. Results of Hybrid FBG with OPC are better than DCF with OPC. Hybrid FBG with OPC may be useful for long distance. On the literature review, back propagation may give the full solution to both linear and nonlinear optical transmission impairments.

III. FUTURE SCOPE

Back Propagation give the joint compensation for Optical Transmission impairments in both Digital (at Receiver) as well as Optical (in line/ transmission channel) mode. In Digital back propagation (DBP), non iterative asymmetric split-step Fourier method (SSMF) uses to solve the non linear Schrodinger equation (NLSE). OBP is better solution to transmission impairments because large bandwidth is offered for OBP, whereas in case of DBP, the bandwidth is limited by the bandwidth of the coherent receiver. DBP demands significant computational resources, especially for wavelength division multiplexing (WDM) system and hence it is currently limited to off-line signal processing. OBP provides real time compensation and it can also compensate for nonlinear impairments in WDM systems. Number of samples per symbol available for DBP is limited by the sampling rate of the Analog-to-Digital converter (ADC). Although it is possible to do up-sampling on the digital signal processor (DSP), it leads to additional computational complexity. However, for OBP, the signal processing is done on the analog optical waveform. OBP requires a real fiber which has loss. So, amplifiers are needed to compensate for fiber loss in the OBP section which increases the noise in the system [9].

IV. REFERENCES

[1]. Agarwal, G P, "Fiber –Optics Communication systems", *A Johan –Wiley & sons, inc. Publication*, 3rd edition.

[2]. Manisha Ajmani and Preeti Singh, "Comparative Analysis of DCF and OPC as Means to Minimise FWM in WDM

System", *Indian Journal of Science and Technology*, vol. 8(27), October, 2015.

[3]. Qiao Yao-Jun et al, "Fiber Nonlinearity Post-compensation by Optical Phase Conjugation for 40 Gb/s COOFDM system", *Chinese Physics Letter*, 2011, vol. 28, No. 6.

[4]. Frederic Lehmann, P. Ramantanis, and Y. Frignac, "Joint Channel Estimation, Interference Mitigation, and Decoding for WDM Coherent Optical Communications", Journal of Optical Communications and Networking, March 2014, Vol. 6, no. 3, pp. 315-325.

[5]. E. M. Ip and J. M. Kahn, "Fiber Impairment Compensation Using Coherent Detection and Digital Signal Processing," *Journal of Lightwave Technology*, vol. 28, no. 4, pp 502-519, Feb.15, 2010.

[6]. Ezra M. Ip et al., "Compensation of Dispersion and Nonlinear Impairments Using Digital Back Propagation", *Journal of lightwave Technology*, vol. 26, No.20, October, 2008.

[7]. Ezra Ip, Alan Pak Tao Lau, Daniel J. F. Barros, Joseph M. Kahn, "Coherent Detection in Optical Fiber Systems", *OPTICS EXPRESS*, vol. 16, No. 2, pp. 753-791, January, 2008.

[8]. Shiva Kumar and Xiaojun Liang, "Optical Back Propagation for Mitigation of Linear and Nonlinear Impairments in Optical Networks", *Journal of Laser Optics Photonics*, November 2016, Vol. 3, issue 3(suppl.).

[9]. Jansen, S.L.," Optical phase conjugation in fiber-optic transmission systems", Technische Universiteit Eindhoven DOI: 10.6100/IR610247.

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