Study and Design of A High Capacity Fiber-Optic Communication Link by Analyzing and Comparing Different Dispersion Techniques Using DCF

M. M.Rahman[1*], M. S. Islam[2], M. M.Tanvir[3], S. Rubayan[4]
[1, 2] Department of Electronic and Telecommunication Engineering
[3, 4] Department of Electrical and Electronic Engineering
Pabna University of Science and Technology

Pabna, Bangladesh

Abstract: **The aim of this thesis work is to design a high capacity fiber optic link. With the increasing growth and demand for the capacity of optical network become an essential part of communication system. The high rate transmission improves spectral utilization which results in increased overall system capacity and reduces the overall cost. The optical communication systems are used as high speed long haul communication systems. To release the potential of communication system and achieve higher transmission capacity at high bit rate, a lot of research on modulates on formats and dispersion compensation schemes has been done. The object of optical fiber communication system is to transmit the maximum number of bits per second over maximum possible distance with fewer errors. Dispersion in the fiber optic link produces the limitations on the optical fiber communication system as well as maximum transmission distance. The main target of this thesis work is to simulate the different techniques used to dispersion compensation and make a comparison between different dispersion compensation schemes in modern optical fiber communication system. Simulation at different transmission speeds or bit rates like- 2.5 Gbps, 5 Gbps, 10 Gbps, 20 Gbps and 40 Gbps. In second approach simulation at constant bit rate but with different fiber length. Two approaches have been accomplished and dispersion compensating fiber (DCF) schemes in pre, post and symmetrical compensation schemes. The efficiencies of the three techniques have been compared on the basis of bit error rate (BER) variations and presented in our final result discussion.**

Keywords: Fiber optic; SNR; Optical dispersion; BER; PMD; SMC channel;

I. INTRODUCTION

A Communication system transmits information from one place to another, whether separated by a few kilometers or distances. Fiber optic communication is a method of transmitting information and data from one place to another by sending pulses of light through optical fiber cable. Information is often carried by an electromagnetic carrier wave whose frequency can vary from a few megahertz to several hundred terahertz. Optical communication system use high carrier frequencies (∼100 Thz), they are sometimes called light wave systems to distinguish them from microwave systems. The light energy which is used in fiber optic communication is not visible for human eyes. The light used in this case has the wavelength (400-1500) nm, but the wavelength of the visible light is (370-750) nm. Fiber-optic communication systems are light wave systems that employ optical fibers for information transmission. The first fiber optic communication is developed in 1970's and have revolutionized the telecom industry because of its advantages over electrical transmission. Optical fiber has largely replaced copper wire communication in core networks.

II. FIBER OPTIC COMMUNICATION SYSTEM

A generalized configuration of fiber-optic communication system is shown in Fig-1. A brief description of each block in this figure will give us an idea of the prime component employed in this system.

i. Information source (input): The information input may be in any of several physical form e.g, voice, video or data. An input transducer is required for converting the non-electrical input into an electrical input. For example, a microphone converts a sound signal into an electrical current. The information input is normally an electrical form for a wired transmission through the fiber optic link.

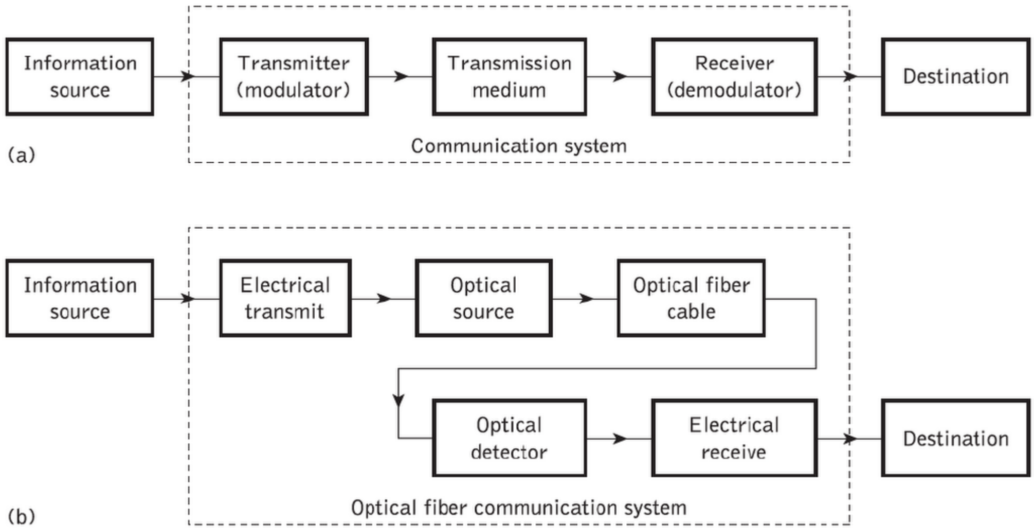


Fig-1: Generalized configuration of a fiber optic communication system

ii. ii. Transmitter: The transmitter comprises an electronic stage which (1) converts the electrical signal into the proper form and (2) impressing this signal onto the electromagnetic wave carrier generated by the optoelectronic source. The modulation of an optical carrier may be achieved by employing either an analog or digital signal. If the information input is in the analog form, an analog-to-digital converter is used to convert it in the digital form.

iii. Optical (Optoelectronic) source: An optoelectronic source generates electromagnetic wave in the optical range which serves as an information carrier common sources for fiber optic communication are light emitting diode (LED) and injection laser diode (ILD).

iv. Optical fiber cable: In fiber optic communication system, the function of a coupler is to collect the light signal from the optoelectronic sources and sent it to the optical fiber cable. At the end of the link again a coupler is required to collect the signal and direct it onto the photo detector. In fiber optic communication the optical signal traverses along the cable consisting of a single fiber or a bound of optical fibers. An optical fiber is designed to transmit the optical signals from the optoelectronic source to optoelectronic detector.

v. Optical detector: The re-conversion of an optical signal into an electrical signal takes place at the OE detector. Semiconductor p-i-n or avalanche photodiode are employed for this purpose. The photo current developed by this detector is normally proportional to the incident optical power and hence to the information input.

vi. Electrical receiver: For analog transmission, the output photocurrent of filtered to remove the dc bias that is normally applied to the signal in the modulator module, and also to block any other undesired frequencies in the signal. After filtering the photocurrent is amplified if needed. These two functions are performed by the receiver module. For digital transmission, in addition to the filter and amplifier, the receiver may include decision circuits. If original information is in analog form, an analog to digital converter may also be required.

vii. Destination (Information output): Finally, the information must be presented in a form that can be interpreted by a human observer. For example, it may be required to transform signal/output into a sound wave or visual image. Suitable output transducers are required for achieving this transformation. In some cases, the electrical output of the receiver is directly useable. This situation arises when a fiber-optic system form the link between different computers and machines.

III. DISPERSION

Dispersion of transmitted optical signal causes distortion for both digital and analog transmission along the optical fiber. Dispersion is the name given to the property of velocity variation with wavelength.

Dispersion mechanism within the fiber cause broadening of the transmitted light pulse as they travel along the channel.

In dispersion phenomenon, each pulse broadens and overlap with its 22 neighbours, eventually becoming indistinguishable at the receiver input. The effect is called are known as inter symbol interference. Does an increasing number of errors may be encounter it on the digital output channel?

The error rate is also a function of the signal attenuation on the link and subsequent signal to noise ratio (SNR) at the receiver.

3. Types of dispersion

Various types of dispersions are discussed latter:

3.1 Intramodal dispersion

Optical sources emit a band of frequencies, then there maybe propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and hence intramodal dispersion occurs. It is also known as chromatic dispersion occurs in all types of fibers. Intermodal or modal dispersion occurs only in multimode fibers. Each type of dispersion mechanisms leads to a pulse spreading. As a pulse spreads, energy is overlapped. Limits the information capacity in the fiber.

Intramodal dispersions are of two types:

3.1.1 Material dispersion: As well known, when a light wave travel in a vacuum, it moves at a velocity of $c = 3*10^8$ m/s. In any other medium, light wave travel at a slower speed, given by $v = c/n$, where n is the index of refraction of the medium. For the material used to make an optical fiber, the refractive index varies with the wavelength of the light traveling inside the fiber. Therefore, a different wavelength of light travels at a different speed inside a fiber. The term dispersion is used to describe the phenomenon of wavelength dependent velocity of propagation of electromagnetic wave. When the velocity variation is caused by some property of the material, the effect is called material dispersion.

3.1.2 Waveguide dispersion: This result from the variation of group velocity with the wavelength in a mode. Each mode that a waveguide will support has a different effective group velocity even through the phase velocity in each different mode may be identical. Chromatic dispersion is the sum of two components: material and waveguide dispersion

3.2 Intermodal dispersion

This type of dispersions Occurs only in multimode fiber. Intermodal all modal dispersion causes the input light pulse to spread. The input light pulse is made up of a group of modes. Pulse broadening due to the intermodal dispersion results from the propagation delay differences between modes within the multimode fiber.

3.3 Polarization mode dispersion

Polarization mode dispersion describes a situation in which the electromagnetic wave components that make up an optical signal travel at different speed within the fiber. This cause a multipath interference at the receiver. PMD is difficult to predict and may possibly vary with temperature and environment, the twisting of cable as it was pulled and even between productions run from the same manufacture. The very high speed system that are soon to be deployed are more prone to failing in the presence of significant levels of Polarization mode dispersion (PMD).

3.4 Dispersion compensation

As described in previous section, attenuation and dispersion effect can significantly limit the bit rate and the spanning distance of fiber optic communication. The war against attenuation can be won because the improvement of fiber manufacturing and invention of fiber amplifier. However, dispersion effect have to be taken into consideration as well. Since PMD rarely observed, modal dispersion is taken by using single mode fiber and waveguide dispersion can be controlled by fiber design, it is the material dispersion usually referred as main factor of limitation of optical network. Several important fiber technologies are used to provide dispersion compensation are described.

Another philosophy is to use standard single mode fiber in combination with a new type of fiber called dispersion compensating fiber (DCF). DCF is a new specialty fiber that has very high negative value of dispersion. It is used is per, post and symmetrical position with the standard fiber. It has disadvantage that is cannot handle high optical power due to its relative small effective area.

IV. DISPERSION COMPENSATION SCHEMES ANALYSIS

Dispersion compensation is very crucial issue for optical communication. Dispersion compensation means compensating or controlling the chromatic dispersion of optical elements. Before detecting the actual signal it is very important to compensate the dispersion with the help of dispersion compensating techniques. For high data rates, pulse broadening or dispersion become much stronger because spectral bandwidth of the signal becomes larger. It is then generally needs to deal with higher-order dispersion. In future, the telecommunication network will be completely composed by optical fibers. Optical communication is a new technology due to its rapid development and the broad range of application. It becomes the denotation of the new technological revolution in the world. As a main transmission of various information tools, it is of great importance in the future information society. Now, optical communication systems are becoming more complex because these systems often include multiple signal channels, different topology structure, nonlinear devices and non-Gaussian noise sources, which make their design, analysis quite complex and require high-intensity work. Optisystem will allow the design and analysis of these systems become quickly and efficiently. We used Optisystem software in analysis for various dispersion compensation schemes.

V. METHODS AND PROCESS

To control the chromatic dispersion in optical fiber is called dispersion compensation and our goal is to avoid excessive broadening and distortion of signals. Pulse broadening and distortion of signals at high data rate, becomes stronger as compare to low data rates due to spectral bandwidth. The dispersion compensation fibers for communication system are being installed at a wide range but the problem with installation of DCFs already existing i.e. for best results where the DCF is to be inserted in channel. The first step will be designing and simulation of the pre, post and symmetric dispersion compensation systems. This will be done by using Optiwave's Optisystem software. Firstly the study about software will be done. The optisystem software is easy to use, flexible, powerful and fast and the optisystem components library includes hundreds 30 of components that enable to enter parameters that can be measured from real devices. By using model design in optisystem software, the parameters such as bit rate, link distance will be varied to achieve best Q-factor. The Comparison analysis of systems will be done by using the optisystem version 7.0. The analysis of Bit Error Rate (BER), Q-factor and eye diagrams is done by using BER analyzer visualizer. In this thesis paper, we will discuss three dispersion compensation techniques to compensate fiber dispersion i.e pre-, post-, and symmetrical compensation. Firstly dispersion compensating fibers (DCFs) is used. After that we present the how dispersion compensation effect the performance of the system. In these simulations, NRZ modulation formats are used and receiver sensitivity is -28 dBm for 2.5 Gbps and -25 dBm for 10 Gbps. We analysis those schemes in various data rate and fiber distance.

VI. VARIOUS SECTIONS AND COMPONENTS

An optical communication system consists of a (1) transmitter, (2) a communication channel, and (3) a receiver, the three elements common to all communication systems

VII. SIMULATION SETUP

The simulation setup designed for dispersion compensation has been designed by using Optisystem 7.0 software Simulations of all the schemes for dispersion compensation (Pre, post, symmetrical) using dispersion compensating fiber (DCF) has been done at various data rates. Parameters listed in table that have been used in our simulations. In the simulation setup, the transmitter section consists of a pseudo random bit generator which generates random stream of 0's and 1's. The output of pseudo random bit generator is fed to NRZ pulse generator which converts binary data into electrical pulses. Next mach modulator is used which modulates the signal from output of NRZ pulse generator with a continuous laser with central frequency at 193.1 THz. The optical link consists of SMF and DCF along with Erbium doped fiber amplifier with s gain 20db. Each span consists of120 km of transmission fiber (SMF) and 24 km DCF in order to fully compensate for the dispersion slope and accumulated dispersion in the transmission fiber. The total length of fiber channel remains same i.e. 144km and two EDFA (Erbium doped fiber amplifier) used in front of transmission fiber and DCF for adjusting the input power level. At the receiver side optical signal is converted to electrical signal by PIN photodiode output of which is fed to a low pass Bessel filter in order to remove high frequency noise from the received signal.

7.1 Pre-Compensation and Post dispersion compensation using DCF

Pre compensation and post-compensation case configuration is shown in figure-2 and figure-3. In dispersion pre compensation dispersion scheme, components are placed in sequence- DCF-SMF this leads to give negative dispersion to pulses when they are transmitted from transmitter and before they enter the SMF channel. In post dispersion compensation system the DCF is placed after SMF which provides pulses to pass through negative dispersion fiber after they have already undergone pulse broadening. In simulations, we have used optical amplifiers after each fiber to compensate dispersion and signal amplification. The dispersion parameter of SMF is 120 km long and 16 ps/nm-km. Therefore, total accumulated dispersion is $16 \times 120 = 1920$ ps/nm. This dispersion can be compensated by using a 24 km long DCF with -80 ps/km-nm dispersion

7.2 Symmetrical Dispersion compensation using DCF

Fiber placement follows the sequence of DCF, SMF, SMF and DCF in symmetrical compensation scheme. In the case of FBG dispersion compensation scheme a post-compensation technique is used because it is simple compared to the symmetrical compensation scheme. All dispersion compensation techniques operate in low power region. Dispersion symmetrical compensation system setup shows in the figure-2.

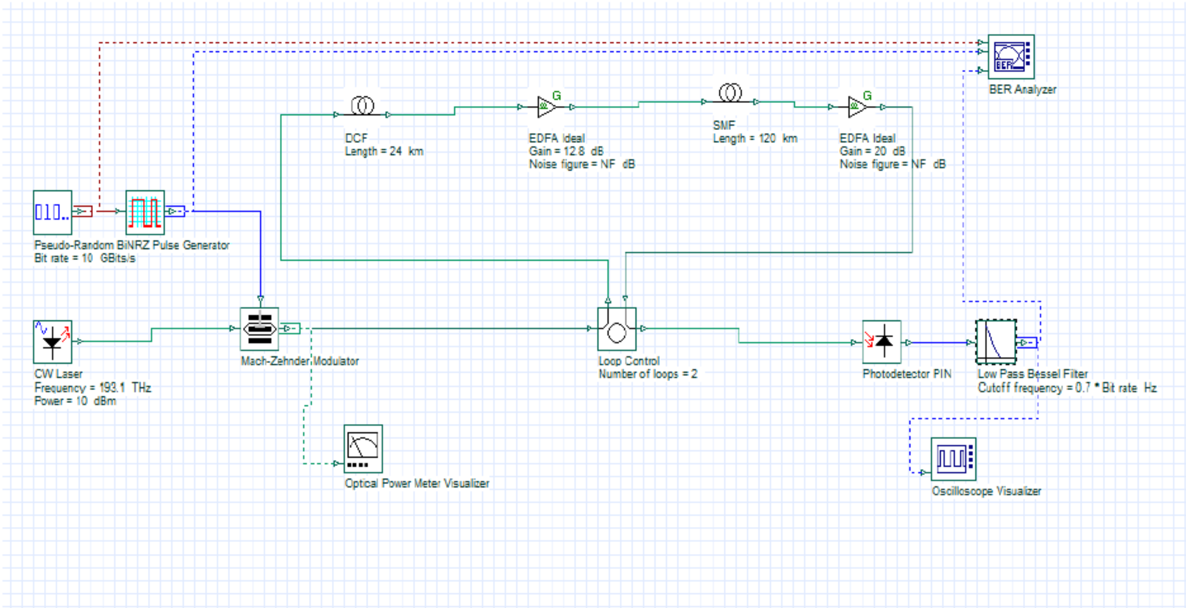


Fig-2.1: Pre-compensation technique

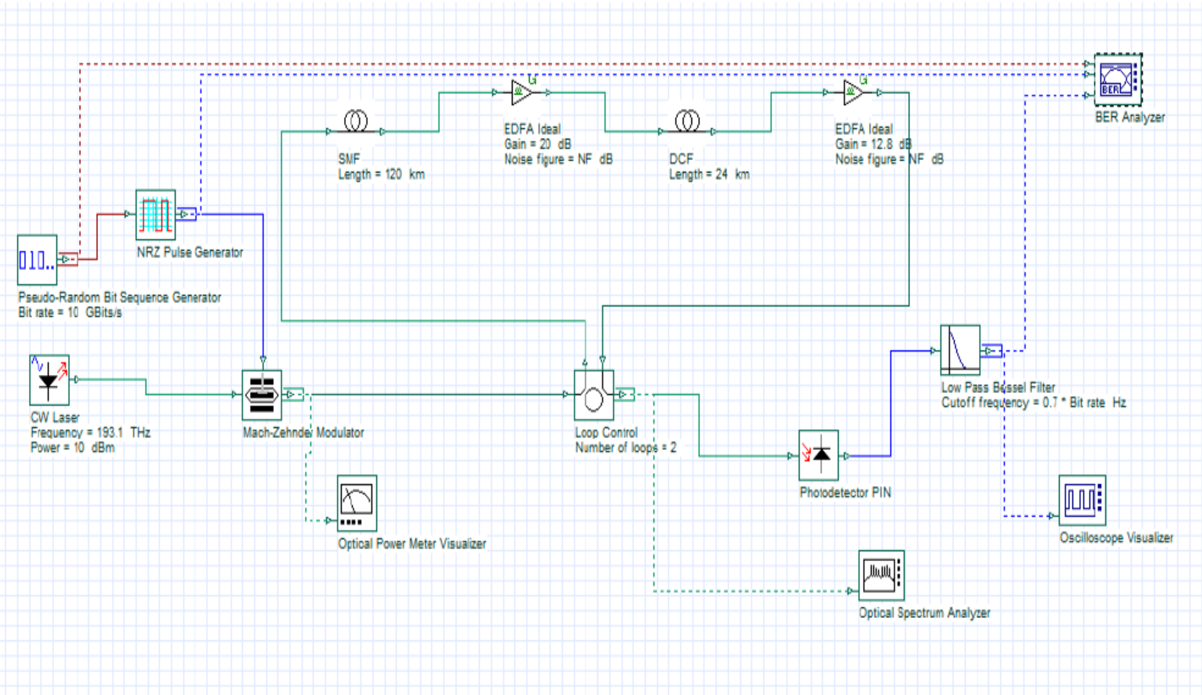


Fig-2.2: Post dispersion compensation

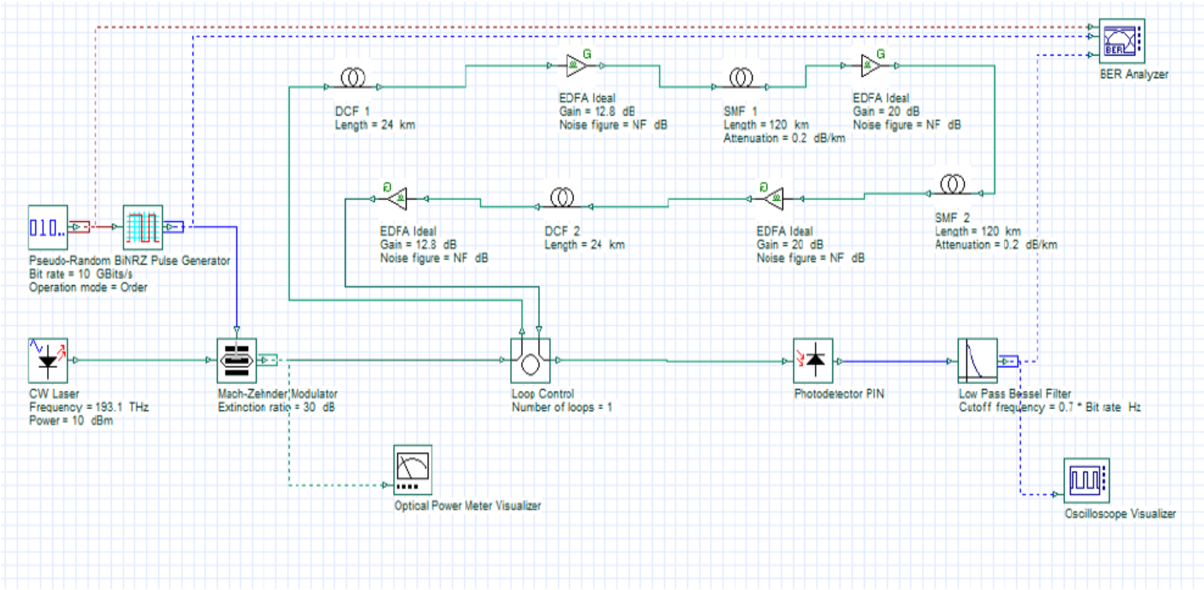


Fig-2.3: Symmetrical dispersion compensation

VIII. VARIOUS PARAMETERS

Table-1: Fiber parameter

Parameter	SMF	DCF
Length (km)	80,100,120,140	24
Attenuation (db/km)	0.6	0.2
Dispersion (ps/nm/km)	16	-80

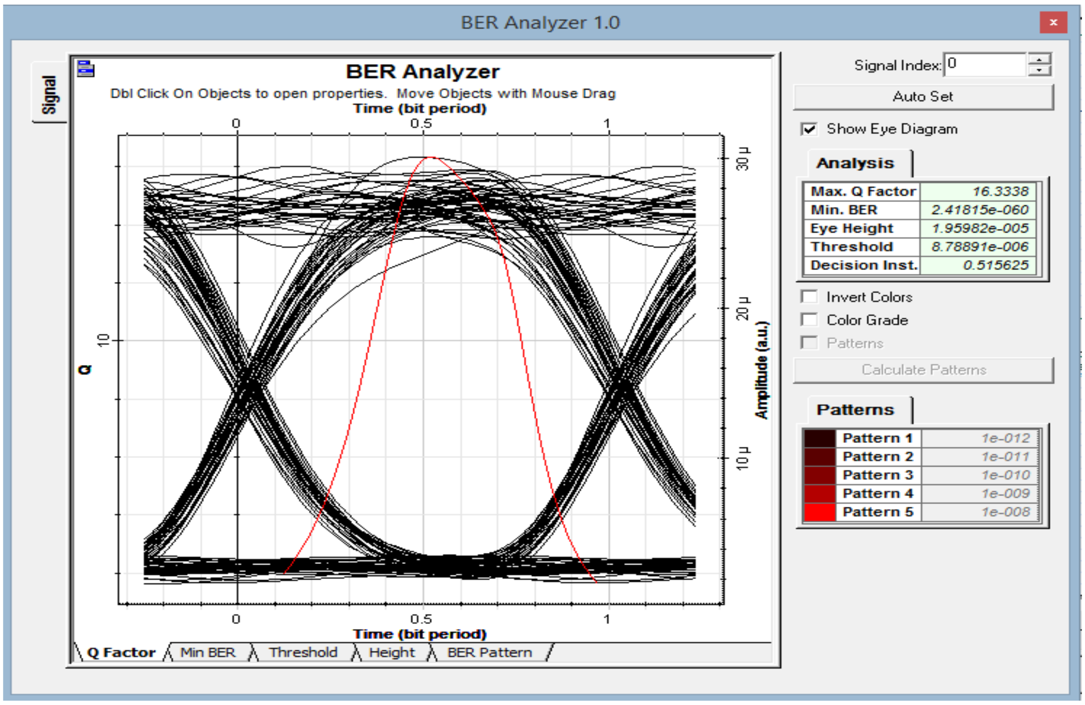
Table-2: Simulation parameter

Parameter	Value
Bit rate (Gbps)	10
Channel frequency (THz)	193.1
Effective gain (dB)	20
Noise figure (dB)	4
Insertion loss (dB)	0
Cut of frequency (Hz)	0.7 $\times$ bit rate

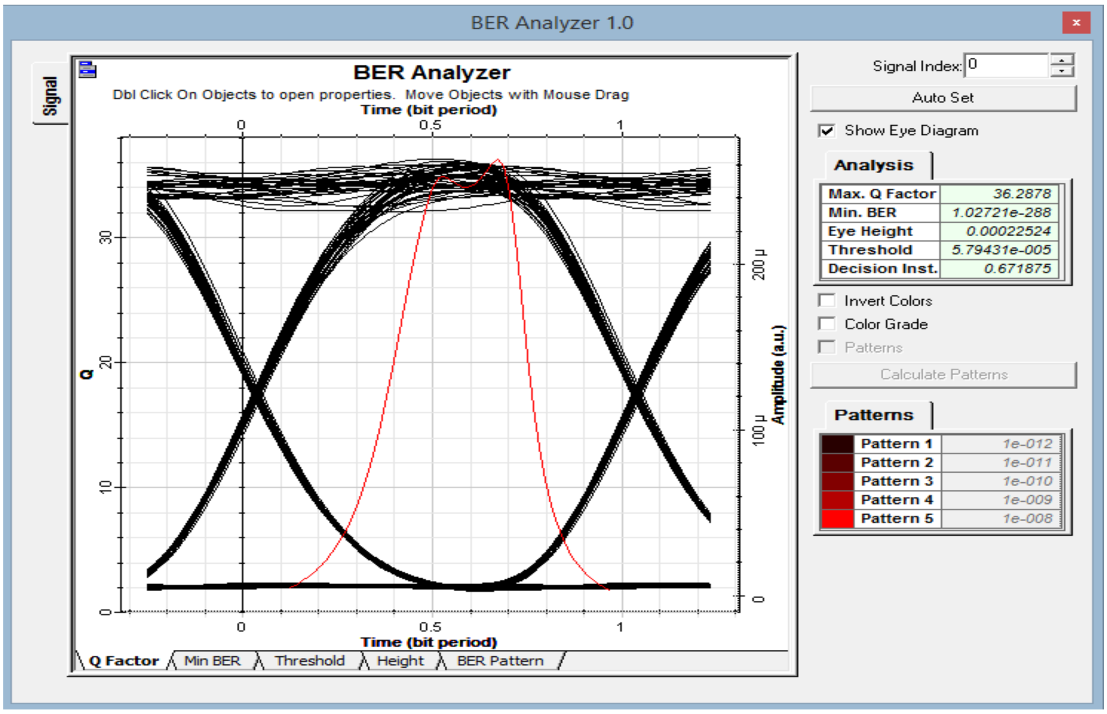
IX. VARIOUS EYE DIAGRAM OBTAINED AFTER COMPENSATION

9.1 Various Eye Diagrams obtained after pre-compensation

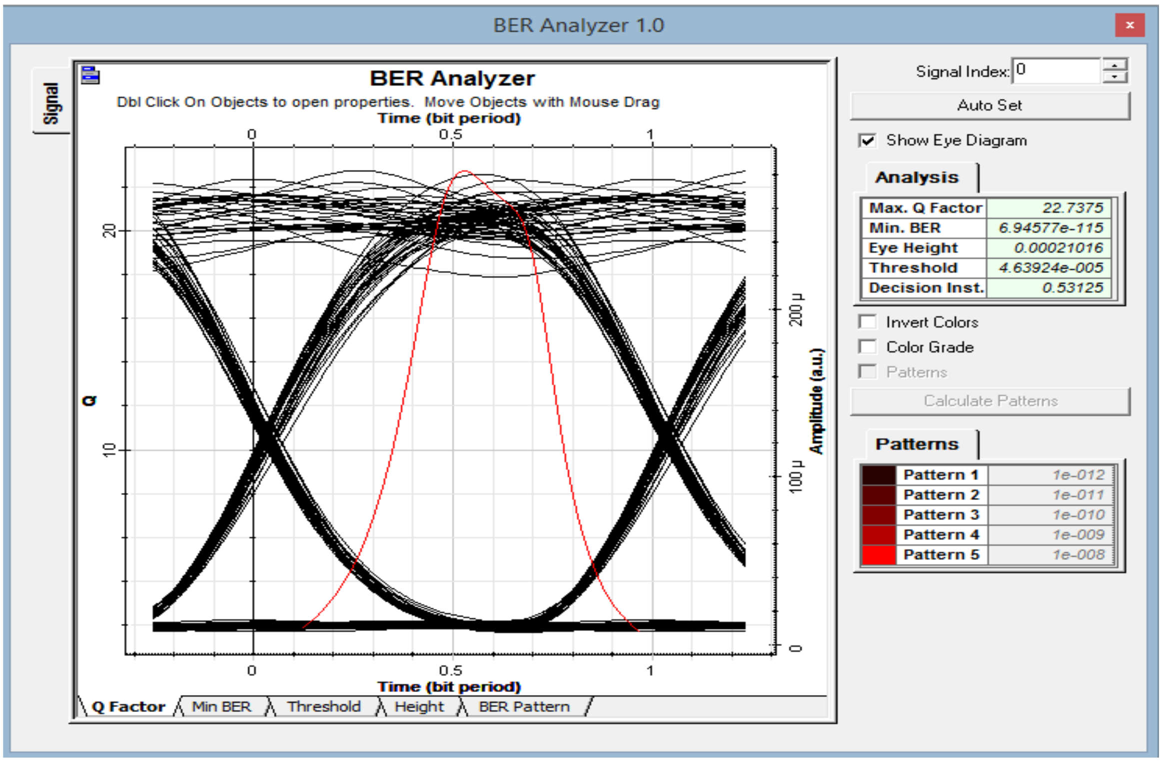
This section shows the various Eye diagrams achieved at output end at BER analyzer. In this Eye diagrams at different power for dispersion compensation techniques like pre compensation scheme, post compensation scheme and dispersion symmetric compensation scheme are observed.


BER Analyzer 1.0
Signal
BER Analyzer
Dbl Click On Objects to open properties. Move Objects with Mouse Drag
Time (bit period)
Q
Amplitude (a.u.)
Q Factor
Min BER
Threshold
Height
BER Pattern
Signal Index: 0
Auto Set
Show Eye Diagram
Analysis
Max. Q Factor 16.3338
Min. BER 2.41815e-060
Eye Height 1.95982e-005
Threshold 8.78891e-006
Decision Inst. 0.515625
Invert Colors
Color Grade
Patterns
Calculate Patterns
Patterns
Pattern 1 1e-012
Pattern 2 1e-011
Pattern 3 1e-010
Pattern 4 1e-009
Pattern 5 1e-008

(a) -5dB


BER Analyzer 1.0
Signal
BER Analyzer
Dbl Click On Objects to open properties. Move Objects with Mouse Drag
Time (bit period)
Q
Amplitude (a.u.)
Q Factor
Min BER
Threshold
Height
BER Pattern
Signal Index: 0
Auto Set
Show Eye Diagram
Analysis
Max. Q Factor 36.2878
Min. BER 1.02721e-288
Eye Height 0.00022524
Threshold 5.79431e-005
Decision Inst. 0.671875
Invert Colors
Color Grade
Patterns
Calculate Patterns
Patterns
Pattern 1 1e-012
Pattern 2 1e-011
Pattern 3 1e-010
Pattern 4 1e-009
Pattern 5 1e-008

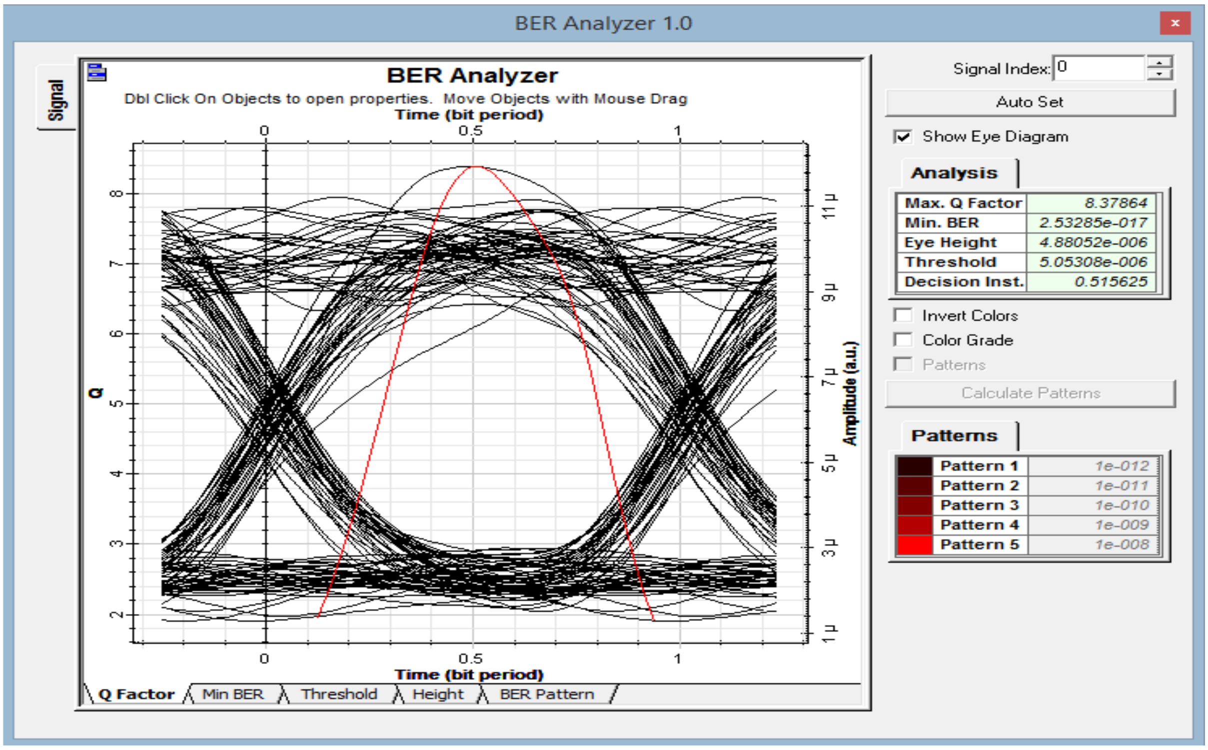
(b) 5dB



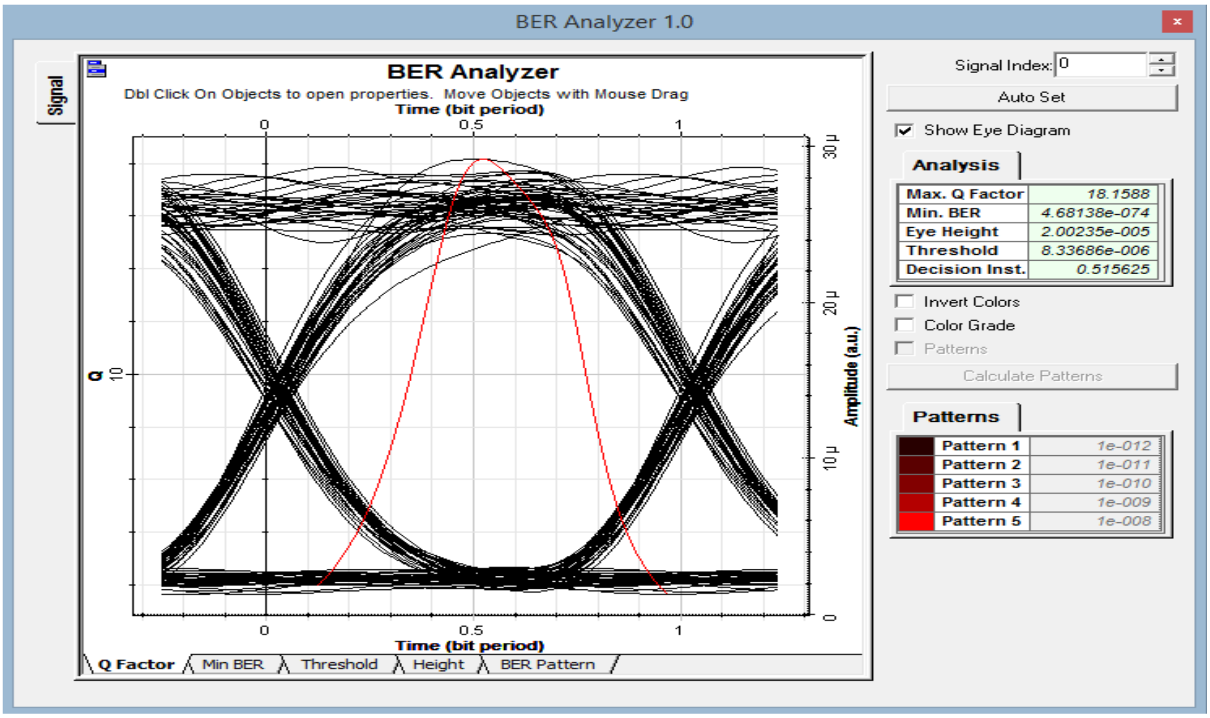
(c)10dB

Fig-3.1: Eye diagram from BER analyzer in pre-compensation where (a),(b) at 2.5Gbps, (c) at 10 Gbps,

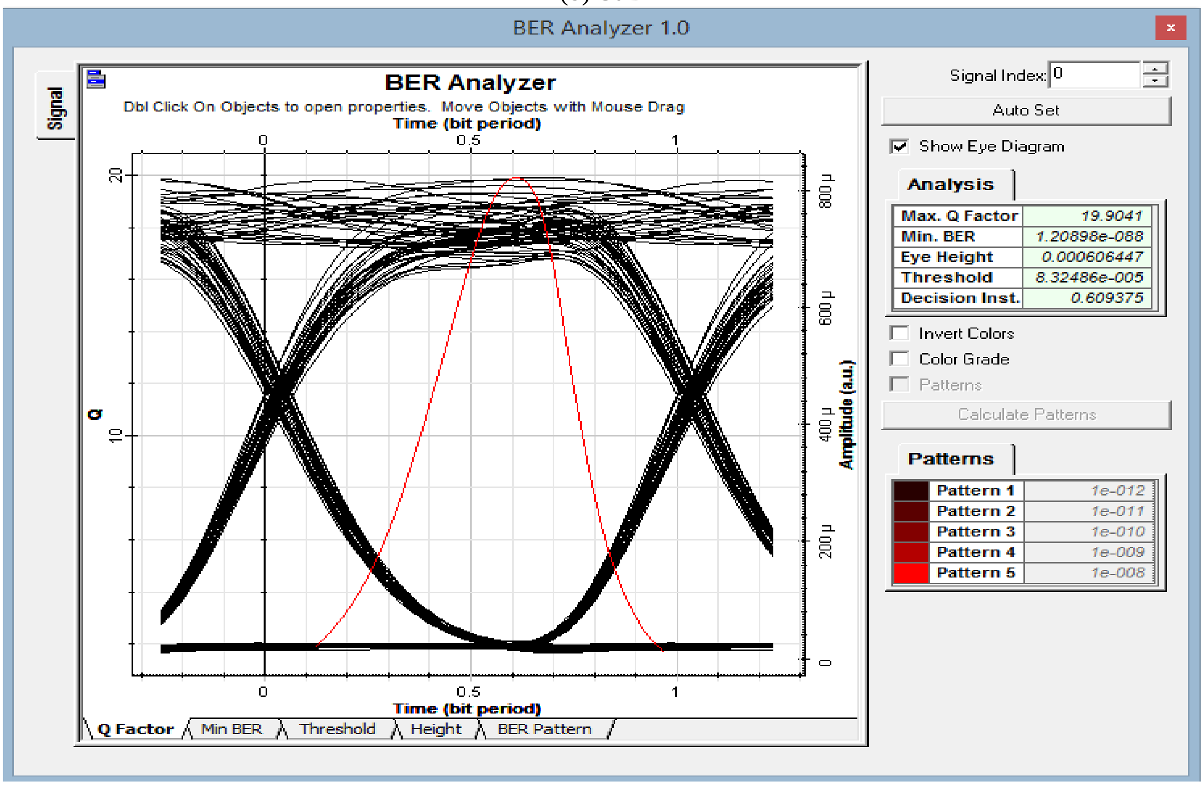
9.2 Various Eye Diagrams obtained after post-compensation



(a) -10dB



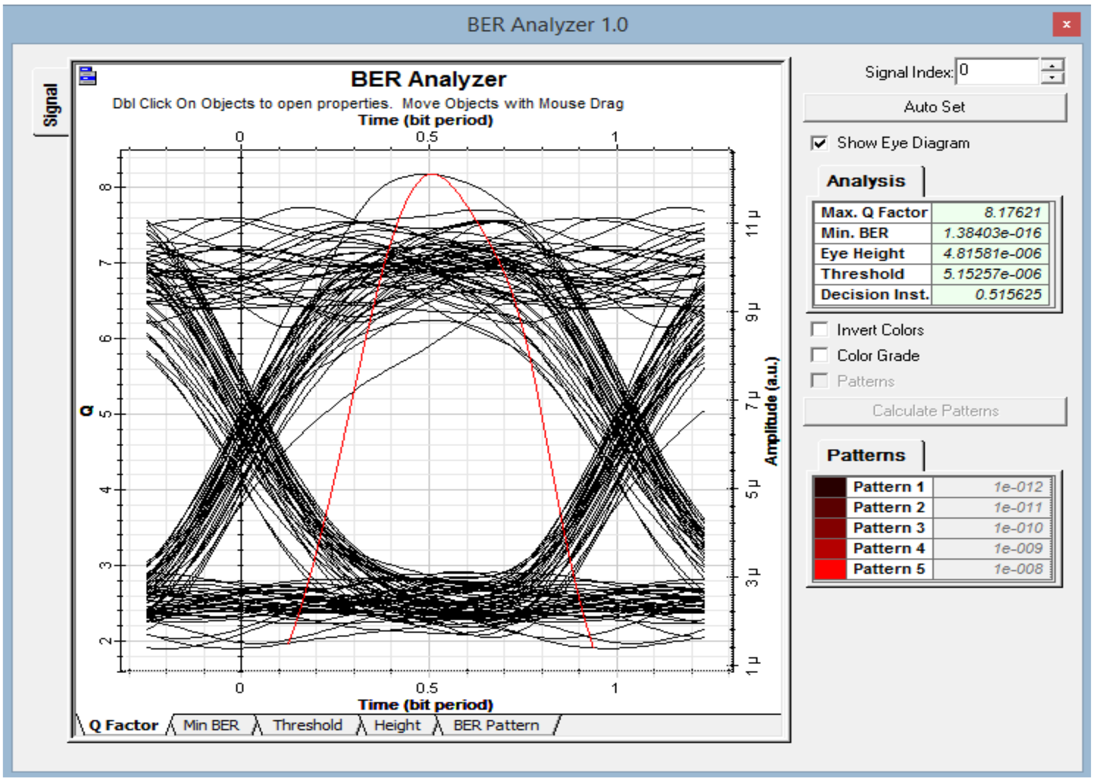
(b)-5dB



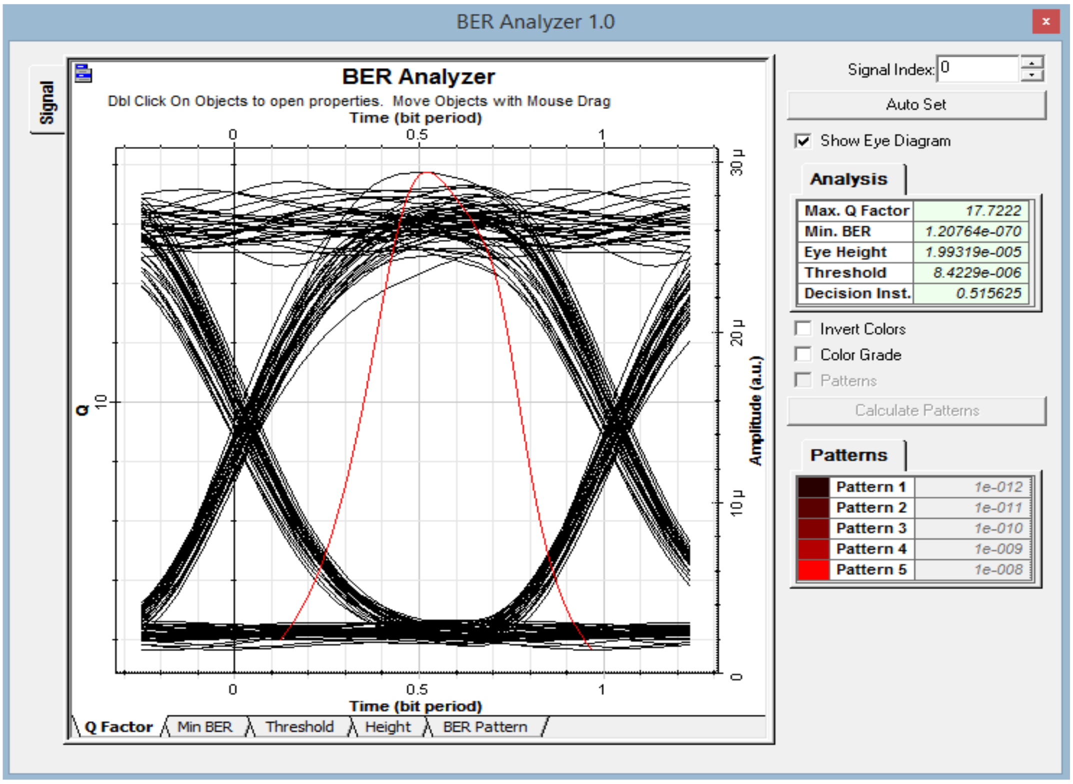
(c) 10dB

Fig-3.2: Eye diagram from BER analyzer in post-compensation where (a) and (b) at 2.5Gbps, (c) at 10 Gbps

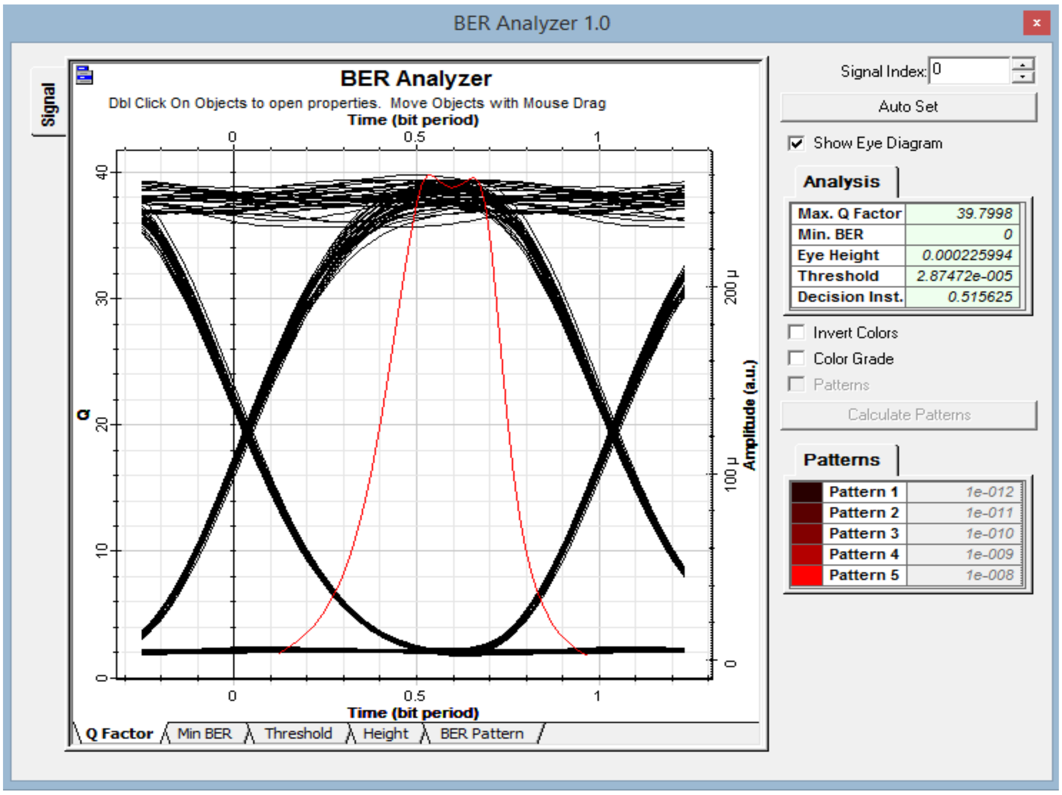
9.3 Various Eye Diagrams obtained after symmetrical-compensation



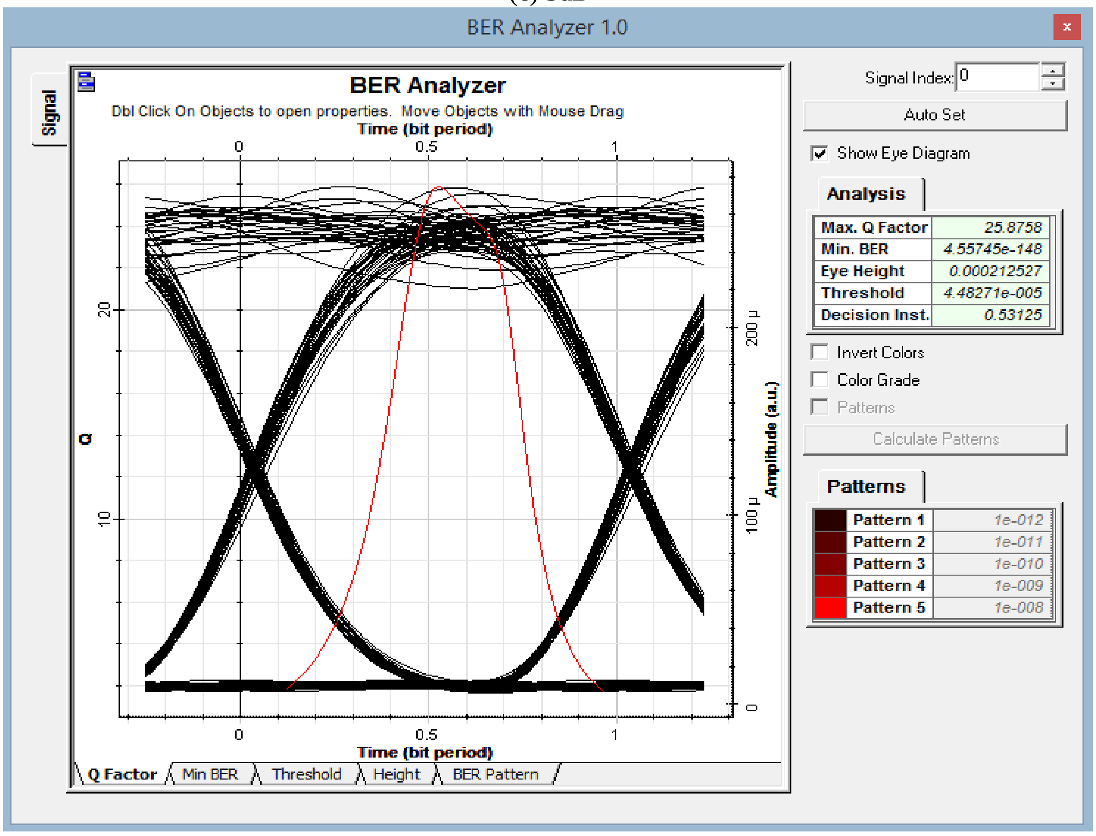
(a) -10dB



(b) -5dB



(c) 5dB



(d) 5dB

Fig-3.3: Eye diagram from BER analyzer in symmetrical-compensation where (a) and (b) at 2.5Gbps, (c) at 5Gbps, (d) 10Gbps

X. SIMULATION RESULT

Simulation results are show in Tables. Tables show Q-factor of received signal versus transmitted signal power for these three different compensation schemes at 2.5Gbps, 5Gbps and 10Gbps, 20Gbps, 40Gbps bit rate. For simulation parameter bit rate 10Gbps need to set and from the simulation outputs we can conclude that symmetrical dispersion compensation gives best performance. Pre-compensation scheme is the worst case out of all three schemes. This can also be seen from the eye diagrams given in above. In pre compensation measurement is taken at varying length at constant bit rate 10Gbps and power 10dB. In post compensation is also done at fiber varying length at constant bit rate 10Gbps. In 80km length done at 5dB. In symmetrical compensation measurement is taken at varying length at constant bit rate 10Gbps and power 10dB.

Table-3 Pre-compensation scheme

Fiber length (km)	Q-factor	Min-BER
80	3.90516	4.66805e-005
100	8.27003	6.4279e-017
120	17.00448	1.2382e-065
140	7.25918	1.61536e-013
160	2.51525	0.00587

Table-4 Post-compensation scheme

Fiber length (km)	Q-factor	Min-BER
80	3.72287	9.82137e-005
100	6.54616	2.8385e-011
120	19.9041	1.20898e-088
140	7.60825	2.19894e-016
160	3.1002	0.000811161

Table-5 Symmetrical-compensation scheme

Fiber length (km)	Q-factor	Min-BER
80	1.73434	0.0392793
100	10.1112	2.41879e-024
120	22.4781	2.26675e-112
140	8.11065	1.15287e-014
160	2.8890	0.00280372

If we are interested in taking the average value of Q-factor for the above three measurement table then we can conclude that symmetrical dispersion compensation gives best performance. Pre-compensation scheme is the worst case out of all three schemes.

10.1 Graphs Comparing Performance Compensation Schemes

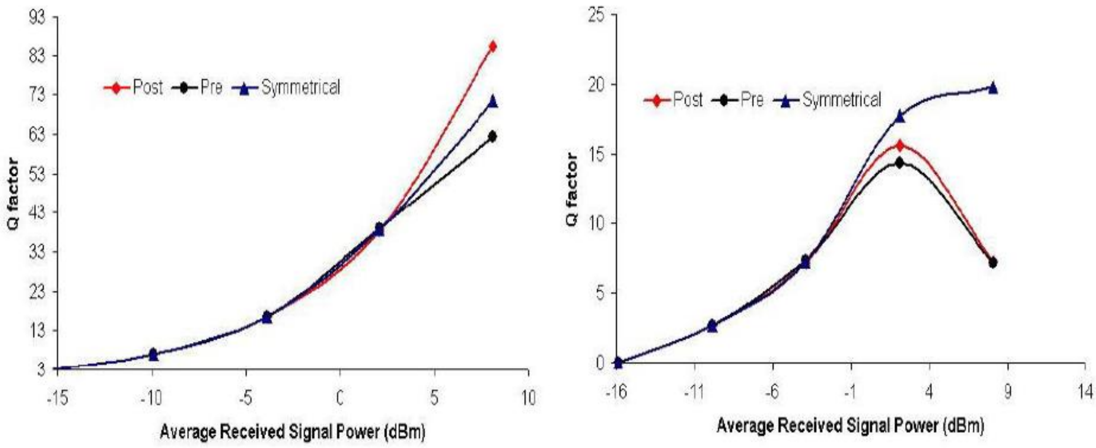


Fig-5.8: Q factor verses signal power for pre-, post-, and symmetrical dispersion Compensations at (left) 2.5Gbps, (right) 10Gbps

10.2 Comparison of results obtained from Simulation from various compensation schemes

Bit rate (Bit error rate)	Parameter	Pre-compensation	Post-compensation	Symmetrical-compensation	Power (dB)
2.5	Q-factor	7.51916	8.37864	8.17681	-10dBm
	Min-BER	2.59784e-14	2.523285e-17	1.38403e-16	
	Q-factor	16.3338	18.1588	17.7222	-5dBm
	Min-BER	2.41815e-60	4.68138e-74	1.20764e-70	
5	Q-factor	36.2878	38.1824	39.7998	5dBm
	Min-BER	1.02721e-288	1.85033e-319	1.25025e-320	
10	Q-factor	17.0448	19.9041	22.4781	10dBm
	Min-BER	1.2382e-065	1.20898e-088	2.26675e-112	
20	Q-factor	14.5194	16.1514	17.1547	5dBm
	Min-BER	3.26957e-048	4.27599e-059	2.08819e-066	

40	Q-factor	10.5341	11.7975	11.8671	5dBm
	Min-BER	2.48811e-026	1.6215e-032	7.24271e-033	

XI. Discussion & Conclusion

This chapter provides a summary of the findings of the study which is done so far. Included in the summary are conclusions from the observations made during the execution of this study. The study of following objectives is reported. The whole designing and development process was passed through. The designing, developing and conducting of technical investigations and experiments of the capstone thesis was tough but enjoyable as I have learn a lot more on fiber optics design.

The first objective of this work is to study the impairments due to dispersion on the performance of the optical fiber communication system. We conclude that optical fibers are subjected to dispersive mechanisms. For a single-mode fiber, we observed that the second-order dispersion coefficient, designated by GVD, is responsible by the broadening that occurs in the pulse propagation inside the optical fiber. The total dispersion can be written as the sum of two terms: the material dispersion and the waveguide dispersion, also known as chromatic dispersion. Dispersion is the major limiting factor in fiber optic communication that limits the bit rate and overall performance. So dispersion compensating schemes are very much necessary in this case. We can use dispersion compensating fiber (DCF) combining with Single mode fiber (SMF) also others are available like fiber brag grating (FBG), optical filters, optical phase conjunction techniques etc. DCF used in three techniques like- pre-compensation, post- compensation, symmetrical- compensation techniques.

The simulation results (eye diagrams, Q factor and BER) show that the technique can reduce significantly the chromatic dispersion resulting in an important increase of the overall performance of the system.

The results of the simulation for pre-compensation, post-compensation & symmetric dispersion compensation systems are presented and discussed in this thesis paper. The performance of the system was analyzed by varying several parameters of the system. In this we compare and analyze the performance of pre, post and Symmetric dispersion compensation system is accomplished successfully. The design and model of pre, post and Symmetric dispersion compensation systems are presented and also model of the systems using OptiSystem software are explained in this research work. We observed the effect of power on dispersion compensation systems. We analyze first at varying fiber length with constant bit rate 10GHz and input power 10dBm in (Table-3, 4, 5). We see that in increasing the SMF length the symmetrical technique is well suited and provide good result. In second case we analyze the optical network at (2.5, 5, 10, 20, and 40) GHz with varying input power provide in (Table-6). We see that at lower bit rate 2.5 GHz and lower power post compensation provide best system performance, but if the bit rate and power is increased the system is observed to give best results for symmetric compensation scheme results in min-BER. The Quality factor observed is in range of 10-100 for symmetric compensation scheme.

From this, it can be concluded that link distance can be increased to greater extents using symmetric compensation techniques as compared to pre and post dispersion compensation techniques. Symmetrical and post schemes provide good performance and pre compensation is the worst case out of all three schemes.

REFERENCES

[1]. Govind P.Agrawal, "Fiber Optic Communication Systems" 3rd Edition, John Wiley & Sons, Inc Publications, 2002.

[2]. Gerd Keiser, "Optical Fiber Communication", 3rd Edition, International Editions, McGraw Hill 2000.

[3]. John M.Senior, "Optical Fibre Communication" 3rd Edition, Prentice-Hall., 2009.

[4]. Palais, Joseph C., "Fiber Optic Communications", Fifth Edition, Prentice Hall, 2005.

[5]. J. Wilson and J.Hawkes, "An introduction to Optoelectronics", 3rd Edition. London, Prentice Hall Europe, 1998.

[6]. Dennis Derickson, "Fibre Optic Test and Measurement", Prentice Hall, 2002.

[7]. Govind P.Agrawal, "Non-linear fiber optics" San Diego: Academic press-1995.

[8]. A.W. Snyder, J.D. Love, "Optical Waveguide Theory", Chapman and Hall, London, 1983.

[9]. D. Marcuse, "Theory of Dielectric Optical Waveguides", Academic Press, San Diego, CA, 1991.

[10]. J C Palais," Fiber Optic Communications", 2nd Edition, PHI OF Cable Installation and external plant for TTA 2008.

[11]. Bernaus J. M. G., Introduction, Slides of course Fiber Optic Communications, UPC, 27 September 2010.
[12]. Jeff Hechf, "Understanding Fiber Optics", 2nd Edition, SAMS Publishing 1996.
[13]. James C.Daly, "Fibre Optics", CRC Press, 1984.
[14]. Roy Blake, "Comprehensive Electronic Communication", West Publishing Company, 1997.
[15]. D J H, Maclean, "Optical Line Systems", John Wiley and Sons, 1996
[16]. Vivek Alwayn, "Optical Network Design and Implementation", Published by Cisco press, Edition 2004.
[17]. Ling Wei Guo, Ying-Wu Zhou, Zu Jie Fang, "Pulse broadening in optical fiber with PMD", Optics communication, pp.83-87, 2003.
[18]. Wei Zhao, "Polarization Mode Dispersion Induced in Optical Fiber", Opt. Lett, vol. 3, pp. 688-690, 2001.
[19]. www.optiwave.com
[20]. www.fiberoptics.com
[21]. www.rp-photonics.com
[22]. www.academypublisher.com
[23]. http://www.fujikura.co.jp/eng/products/tele/o_fiber/td101001.html
[24]. Wave Optics, Single Mode Optical Fibers: http://www.waveoptics.com
[25]. B. Wedding, B. Franz, and B. Junginger, "10 Gb/s optical transmission up to 253 km via standard single-mode fiber using the method of dispersion supported transmission," J.
[26]. Light wave Technology, vol. 12, pp. 1720-1727, 1994.

[27]. Warsha Balani and Manish Saxena (2013),"EDFA Gain Performance analysis at 2Gbits/sec in Optical Transmission System", IJMCR, pp. 20-28.
[28]. R.S. Kaler, Ajay K. Sharma, T.S. Kamal, "Comparison of pre-, post- and symmetrical-dispersion compensation schemes for 10 Gb/s NRZ links using standard and dispersion compensated fibers," Optics Communications, Vol. 209, Issues 1-3, pp. 107–123, 2002.
[29]. Ladislav Stepanek, "Chromatic Dispersion in Optical Communications", Vol. VII, No. 2, pp. 142-151, July 2012.
[30]. Thyagarajan (2007) "Pulse Dispersion in Multimode Optical Fibers", Fiber Optic Essentials, Thyagarajan/Fiber Optics.
[31]. K. Kazaura, K. Wakamori, M. Matsumoto, T. Higashino, K.Tsukamoto and S. Komaki, "RoFSO: A universal platform for convergence of fiber and free-space optical communication networks," Communications Magazine, IEEE, vol. 48, 2010, pp. 130-137.