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Study and Simulation of Different DCF configurations in Optical Fiber Communication Link

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Abstract

Dispersion is one of the basic problems in the optical fiber communication. Chromatic dispersion is one of this type of dispersion. Nowadays we require high data transmission without any substantial loss in a communication system, so optical communication serves as a better choice for high data rate transmission. However, it has a dispersion problem. To overcome dispersion in an optical communication system, we propose a new approach to reduce further the chromatic dispersion based on using Dispersion Compensating Fibers (DCF). The proposed approach consists of splitting the fiber link into different configurations and investigate each configuration by simulation in order to determine the most appropriate one with regard to the Quality-Factor and Bit Error Rate. The obtained eye diagrams confirm achievement of complete reduction of chromatic dispersion in the fiber at long distance communication. Optisystem version 7.0 is used as a software tool for experimental validation of the proposed approach.

Dedication

First and foremost, thank to Allah for his uncountable blesses. Joy would not feel good if it was not for pain, after all this hard work we are really happy for this achievement.

We dedicate this work to our parents, siblings and friends and every one stood by our side in this life.

Acknowledgement

First, we would like to thank our supervisor Dr. Abdelkader ZITOUNI for introducing us to this theme and for his guidance and useful advises through the process of these work . We thank also everyone that help us at least with a word in this project.

Acronyms

ADSL: Asymmetric Digital Subscriber Line.

APD: avalanche photodiode.

BER: bit error rate.

CATV: Community antenna television

CD: Chromatic Dispersion.

CDM: Code Division Multiplexing.

CW: continuous wave.

DCF: dispersion compensating fiber.

DEMUX: DE-Multiplexer.

EDFA: erbium-doped fiber amplifiers.

FBG: Fiber Bragg Grating.

FDM: Frequency Division Multiplexing.

FSO: Free space optic.

FSR: free spectral range.

IoT: Internet of Things.

LAN: Local Area Network.

LASER: Light Amplification by Stimulated Emission of Radiation.

LED: light emitting diode.

MAN: medium area network.

MMF : multimode fiber.

MUX : Multiplexer.

MZM: Mach-Zehnder modulator.

NRZ: Non-return to Zero.

PMD: Polarization mode dispersion.

PON: Passive optical networks.

ROF: Radio over fiber.

SDH: Synchronous Digital Hierarchy.

SMF: single mode fiber.

SNR: Signal-to-noise ratio.

SONET: Synchronous Optical Network.

WDM: wavelength division multiplexing.

Wi-Fi: Wireless Fidelity.

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GENERAL INTRODUCTION

Introduction:

In a communications system the transmitter sends a message to the receiver through a communication medium. In fiber optic communication is transmitted pulses of light through an optical fiber, where the light forms an electromagnetic carrier wave that is modulated to transport information. This way the fiber optic is the medium, and the light pulses the message. The three principal components of a fiber optic communication system are: the optical transmitter, the fiber optic and the optical receiver.

Fiber optics communication is preferred because of low cost, high transmission speed, less maintenance required and etc. but problems like attenuation, dispersion, non-linear effects which leads to decrease in performance of the optical fiber. Attenuation and dispersion limit the performance of optical fiber as data transmission channel. Attenuation, associated with losses of various kinds, limits the magnitude of optical power transmitted. Dispersion, which is responsible for temporal spread of optical pulses, limits the rate at which such data-carrying pulses may be transmitted.

Due to the rising population the number of users is increasing day by day. To fulfil the requirement of this rising population the system has to be more efficient. The efficiency can be increased by the help of WDM (Wavelength Division Multiplexing). In this technology the number of wavelengths is combined onto the same fiber which increases the capacity of the fiber network dramatically. WDM network is also affected by dispersion, attenuation nonlinear effects. Amplifiers are used to amplify the transmitted signal and to reduce the loss.

The optical fiber communication system consists of 3 sections and they are transmitter section, medium and the receiver section. The medium mainly contains optical fiber and optical amplifier. The light signal travels in the optical fiber, while passing through the fiber it faces dispersion. Dispersion keeps on increasing along the length of the optical fiber. In this paper we have discussed about dispersion and dispersion management using DCF.

- **Chapter 1:** introducing optical communication systems and optical fiber technology, describes deferent components such as transmitter receiver and deferent properties and types of optical fiber.
- **Chapter 2:** defining dispersion and it types and how to deal with it.
- **Chapter 3:** simulating our system and discussing the results.
- **Chapter 4:** summarising our results and ending up with a general conclusion

CHAPTER 1:

OPTICAL COMMUNICATION SYSTEMS

1. Introduction:

Fiber optic is the passing of light through a plastic or a glass fiber so that it can be directed to specific location. If the light is modulated with an information signal, then that signal is transmitted over the optical path, as figure 1.1 shows.

An optical fiber is a thin flexible transparent that act like waveguide or light carrier to transmit light between the two ends of the fiber. optical fibres are widely used in fiber optical communications which permits transmission over longer distances with a higher bandwidth or data rate than other forms of communication. fibres are used instead of meter wires because signals travels along them with less loss and are also immune to electromagnetic interference. [1]

Figure 1.1 : basic configuration of optical fiber communication

2. Optical Transmitter:

The role of the optical transmitter is to: convert the electrical signal into optical form, and. launches the resulting optical signal into the optical fiber which acts like communication channel. optical transmitters consist majorly of optical source. Optical fiber communication use often semiconductors optical source such as light emitting diodes (LEDs) and semiconductors lasers.

2.1. LED Transmitter:

A LED is a forward biased p-n junction semiconductor that emits light when a current pass through it. the main portion in a LED is the semiconductor chip which is separated into two regions by a boundary called the junction. The p region is dominated by the positive charges(holes) and the n region is dominated by the negative charges (electrons). the electrons move from the n region to the p region through junction. Band gaps determine the energy needed for the electron to leap from the valance band to the conduction band. The transition of electrons to a lower lying energy state releases energy as photons equal to the band gap energy. [2]

The relation between the band gap and he wavelength of the emitted light is shown in equation 1.1:

$$\lambda = hc \, / \, E_p \qquad (1.1)$$

λ: the wavelength of the emitted light

h: Planck's constant

c: speed of light

E_p: the energy of photons

2.2. Laser Diode:

LAER stand for 'light amplifier by stimulated emission of radiation'. Laser diodes are semiconductor p-n junction that converts electrical energy to optical radiation similar to LEDs. the wavelength of the output radiation depends on the energy gap too however the laser output is highly coherent and can be collimated, while the LED output radiated in many directions.

3. Optical Fiber:

A fiber-optic cable is thin glass or plastic cable that acts as a light "pipe." It is not really a hollow tube carrying light, but a long, thin strand of glass or plastic fiber. Fiber cables have a circular cross section with a diameter of only a fraction of an inch as demonstrated in figure 1.2. Some fiber optic cables are the size of a human hair. A light source is placed at the end of the fiber, and light passes through it and exits at the other end of the cable. How the light propagates through the fiber depends upon the laws of optics [3].

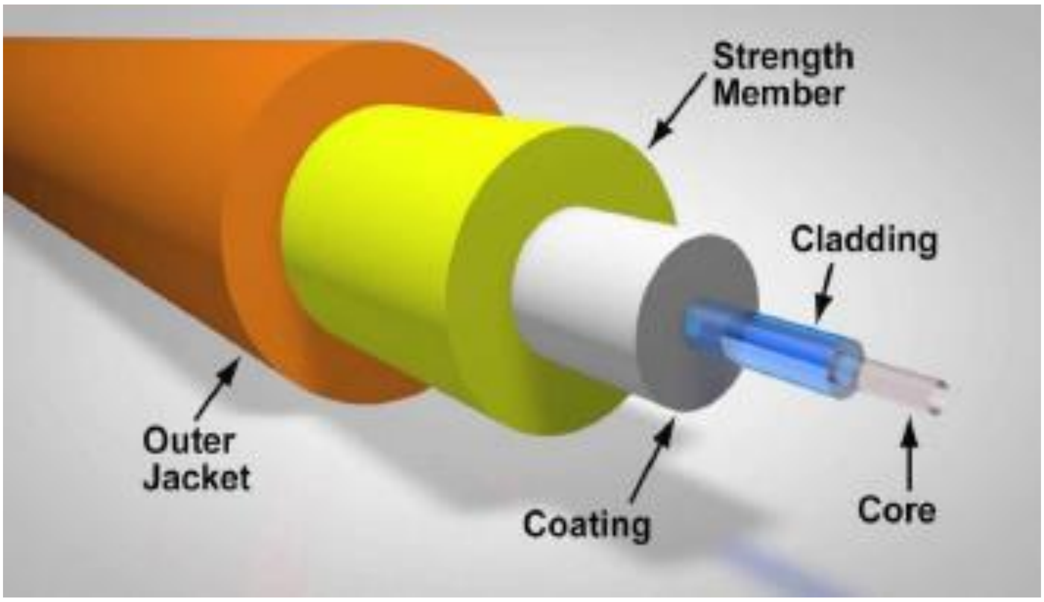


Figure 1.2 : structure of an optical fiber [3]

The phenomenon of total internal reflection, responsible for guiding of light in optical fibers, is known since the nineteenth century [3], by Snell's law:

$$n_0.\ \sin\theta_i = n_1.\ \sin\theta_r \qquad (1.2)$$

n_0, n_1: the refractive indices of the air and the core respectively

θi, θr: the incident angle and the refractive angle respectively

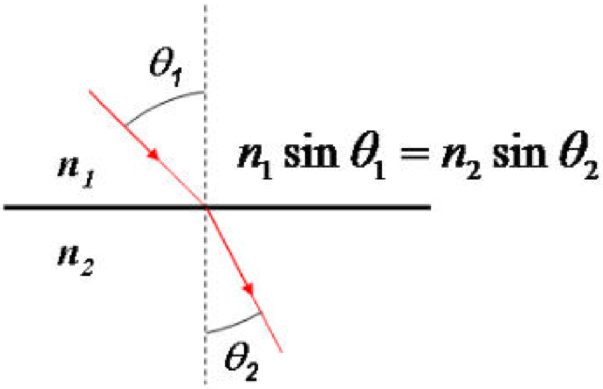


Figure 1.3 : illustration of snells-law

By applying this law on the core and the cladding we get:

$$\sin\emptyset c = \frac{n_2}{n_1} \qquad (1.3)$$

n_2: the refractive index of the cladding

$\emptyset_c$: the critical angle

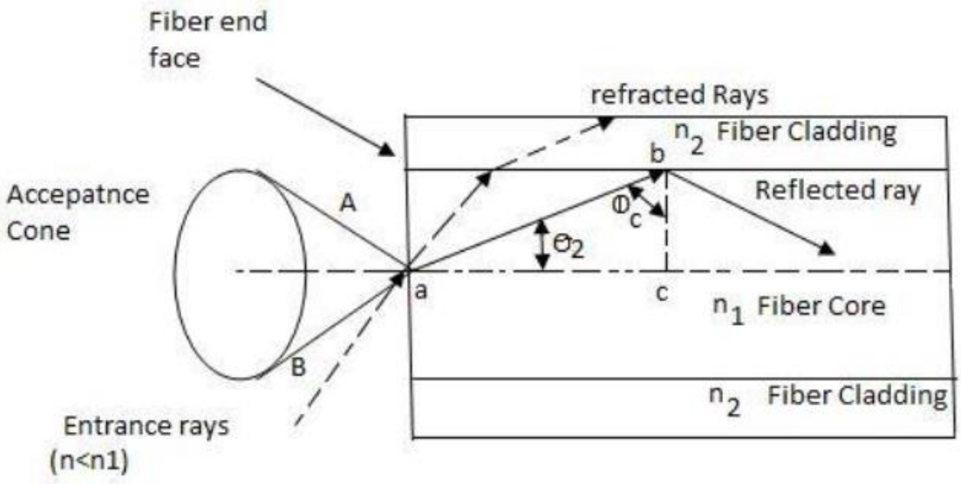


Figure 1.4 : signal propagation in optical fiber

There are two main types of optical fiber in optical communication single mode fiber (SMF) and multimode fiber (MMF):

3.1. Single Mode Fiber:

Single-mode fibres are optical fibres designed to support only a single mode per polarization direction for a given wavelength, the core diameter is typically between 8 and 9 µm, while the cladding diameter is 125 µm. For single-mode fiber, a smaller core makes it possible restrict the light propagates in one mode or one path only down the fiber [4].

3.2. Multi-Mode Fiber:

Multi-mode fiber, by comparison to single mode fiber, is manufactured with core diameter as small as 50 µm and as large as hundreds of micrometres. the two types of fibers used for multimode application are step index and graded index. a step index fiber has constant values of both the cladding and the core refractive indices.in a graded index fiber, the refractive index of the core is not constant that decreases gradually from its e maximum value n1 at the core centre to its minimum value at the core-cladding interface.

The MMF core radius is large, therefore, it is easier to launch the optical power into it and also to splice two MMFs. Furthermore, light can be launched to the fiber from an inexpensive optical source that has a large angular spread such as an LED. In addition to that, its channel capacity is large because, in principle, each mode of a MMF can carry as much information as a single SMF [5].

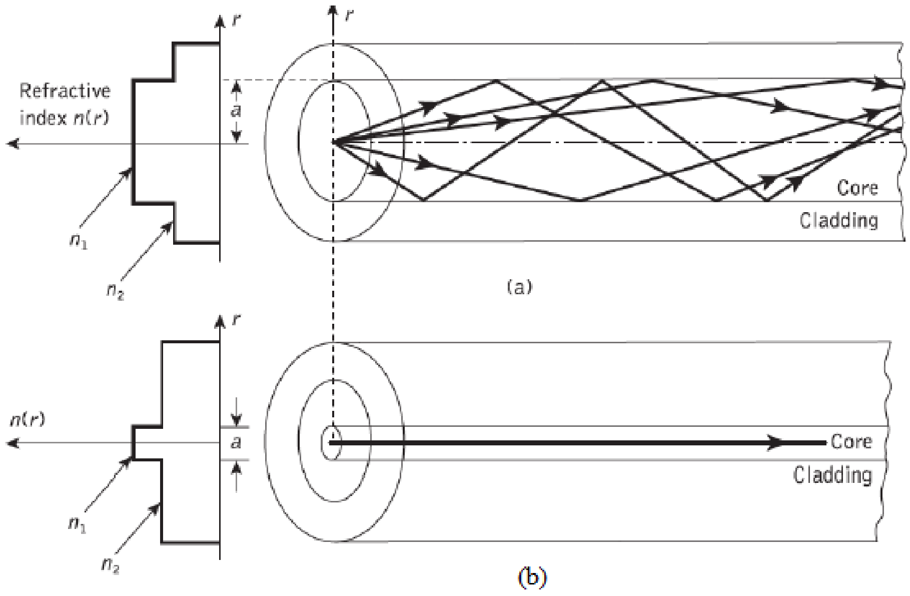


Figure 1.5: a) Multimode fiber b) Single mode fiber.

4. Optical Receiver:

The function of an optical receiver is to decode and interpret the optical signals and generate an electrical data stream proportional to the received optical signal. The main component of an optical receiver is a photodetector, which converts the optical power into electrical current. Photodetectors need to meet stringent requirements to achieve desirable performance. Requirements include good responsivity (sensitivity) to a wide range of wavelengths used for transmission (usually in the 850 nm, 1300 nm, or 1550 nm region), low noise characteristics, low or zero sensitivity to temperature variations, low cost, and extended operating life. Even though several types of photodetectors are available, semiconductor-based photodetectors (photodiodes) are used exclusively for optical communications. The most common photodiodes used in optical systems are PIN photodetectors and Avalanche Photo Detectors (APDs), due to their small size, fast response, high photo-sensitivity and comparably low costs [6].

4.1.PIN Photodetector:

The PIN diode is an extension of the P-N junction diode, in which slightly doped intrinsic material (I stands for intrinsic) is inserted in between the P-N junction, thereby increasing the depletion width (region) of the P-N junction

A high reverse-biased voltage is applied across the PIN diode so that the intrinsic region is completely depleted. Figure 1.5 represents the normal operation of a PIN diode with reverse bias applied across the p-i-n junction. When light (photons) is incident on a semiconductor material, electrons in the valence band absorb it. As a result of this absorption, the photons transfer their energy and excite electrons from the valance band to the conduction band, leaving holes in the valance band.

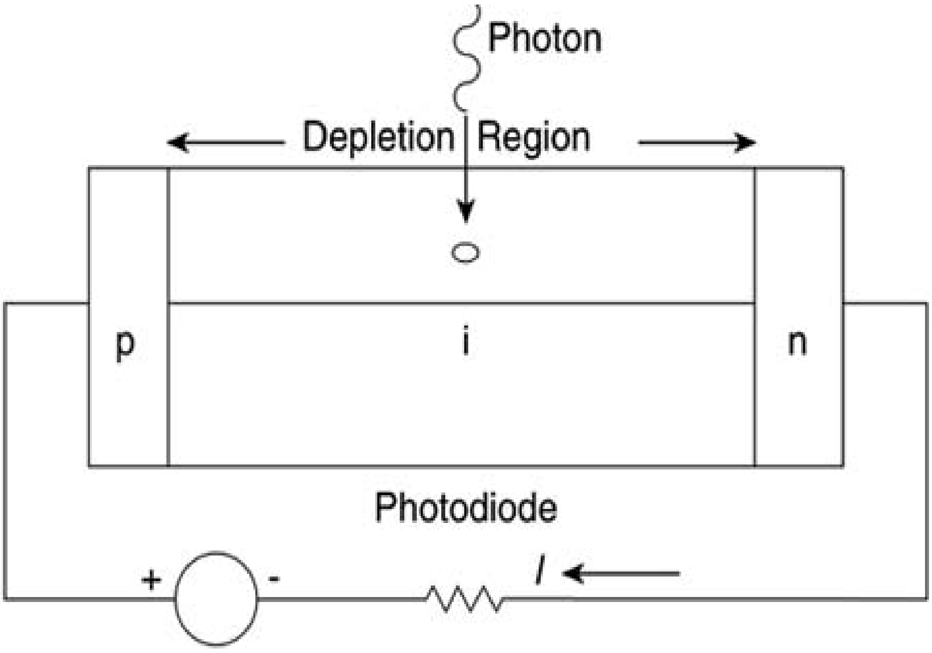


Figure 1.6: PIN photodiode

4.2.Avalanche Photodiode:

When light is absorbed by a PIN photodetector, only a single electron hole pair is generated per photon. You can increase the sensitivity of the detectors if more electrons are generated, which means that you need less power for photodetection and that the signal can travel longer.

If a high electric field is applied to the generated electrons, enough energy is procured to excite more electrons from the valence band to the conduction band. This, in turn, results in more electron hole pairs being generated. These secondary electron hole pairs that are generated by the preceding process can produce more electron hole pairs if they are subjected to a high electric field (Avalanche effect).

This process of multiplication of electron-hole pairs is called avalanche multiplication. the photodiode that is designed to achieve this electron-hole pair multiplication is known as avalanche photodiode (APD) [6].

5. Optical Amplifier:

Optical amplifiers amplify incident light through stimulated emission, the same mechanism as used with lasers. These amplifiers are the same as lasers without feedback. Optical gain is achieved when the amplifier is pumped either electrically or optically to realize population inversion.

There are semiconductor laser amplifiers, Raman amplifiers, Brillion amplifiers, and erbium-doped fiber amplifiers (EDFAs). Certainly, the EDFAs show the widest acceptance. One reason is that they operate near the 1.55-mm wavelength region, were fiber loss is at a minimum. Reference 11 states that it is possible to achieve high amplifier gains in the range of 30 dB to 40 dB with only a few milliwatts of pump power when EDFAs are pumped by using 0.980-mm or 1.480-mm semiconductor lasers [7].

6. Optical Modulation:

Modulation can be defined by superimposing of a data onto a carrier signal by altering one of the virtues of the carrier signal with respect to a change in the data stream.in other words, you can make a binary data stream superimposed on a carrier frequency. the motive behind modulation is to enable transport of data efficiently and without many errors. In an optical WDM network, data is modulated onto the light that a laser diode emits. One way of modulation g is to make the output optical power of a laser diode proportional to the binary sequence of the data stream. Two methods are commonly used in order to perform the electro-optical conversion: direct and external modulation. With direct modulation the output power of the light source (a light-emitting diode or a laser) is directly proportional to the electrical input signal. One of the main advantages of using direct modulation is that is cheap and simple to implement. It does however have some disadvantages; the switching of the input current causes a variation of the instantaneous frequency which leads to a chirp effect and the modulation speed is very low (normally not higher than 10 Gb/s). With external modulation an external device is responsible for modulating the intensity and/or phase of the optical source, the laser emits a continuous wave. External modulation is typically used in high-speed transmission systems such as long-haul telecommunication systems. The main advantage of such modulation is the high modulation speed achieved and less chirping effects than when using direct modulation.

- Mach-Zehnder modulator configuration:

one of the most common external modulators used is the Mach-Zehnder modulator which is a device composed of a divider, two optical fiber arms and a combiner. It is based on the wave

interference phenomenon, the incoming optical signal is split into two signals, each one going through a different optical path, that then are recombined. The recombination produces constructive interference if the phase difference between the two signals is zero, if the phase difference between the combined signals is equal to *the* signals will interfere destructively and the output light intensity will be near zero. The waveguides on each arm are made out of an electro-optical material, typically lithium niobate (LiNbO3), whose refractive index changes when an external voltage is applied to two electrodes placed on both sides of the waveguide. Changing the applied voltage causes phase shifts variations between the recombined signals and thus modulates the optical input signal.

The transfer function of a MZM is given by [8]:

$$\frac{Eout(t)}{Ein(t)} = \frac{e^{j\varphi 1(t)} + e^{j\varphi 2(t)}}{2} \qquad (1.4)$$

where$\varphi 1(t) = \frac{\pi V1(t)}{V\pi}$ (1.5)and $\varphi 2(t) = \frac{\pi V2(t)}{V\pi}$ (1.6) represent the phase shift in both arms of MZM. The difference between the maximum and the minimum in the transfer function of the MZM is defined by $V\pi$, which is one of the most important parameters to characterize these modulators.

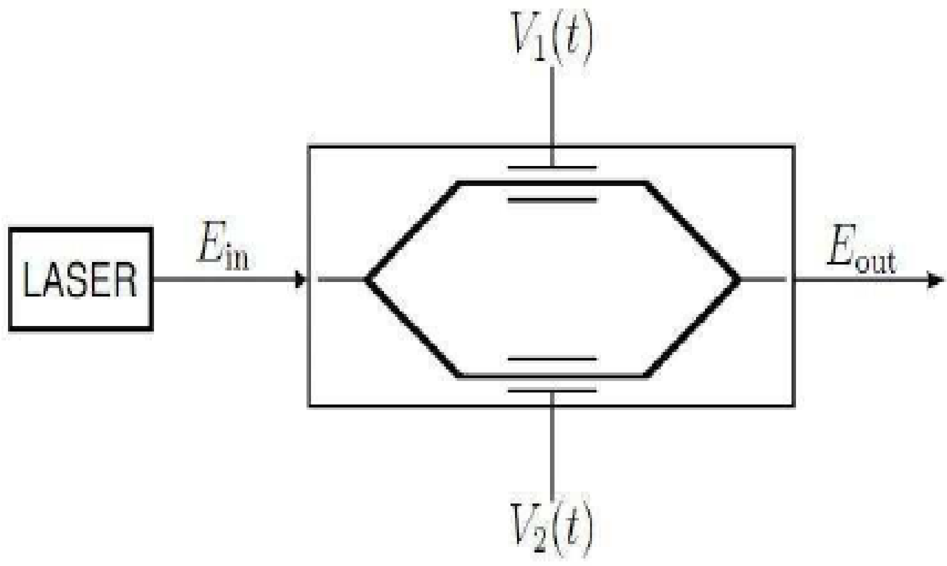


Figure1.7: Mach Zehnder modulator

7. Transmission Characteristics of The Optical Fiber:

Optical receivers need a certain minimum amount of power for recovering the signal accurately, the transmission distance is inherently limited by fiber losses. Attenuation and pulse dispersion represent the two most important characteristics of an optical fiber in determining the information-carrying capacity of a fiber optic communication system [9].

7.1. Attenuation:

Attenuation in an optical fiber is defined as the decrease in light power during light propagation along an optical. it is also known as fiber loss or signal loss in an optical fiber. It's mainly a result of light absorption, scattering and bending losses. it determines the maximum repeater less separation between the transmitter and the receiver. Due to attenuation, the power of light wave decreases exponentially with distance. If an input power P_1 results in output power P_2, the loss in decibels is given by:

$$\alpha = 10 \log 10 \left(\frac{P_1}{P_2}\right) \text{dB/km} \qquad (1.7)$$

Optical loss in optical fibers is one of the two main fundamental limiting factors as it reduces the average optical power reaching the receiver. The optical loss is the sum of three major components intrinsic loss, micro bending, loss and splicing loss [9].

7.2. Material Absorption:

Material absorption accounts for the imperfection and impurities in the fiber. The most common impurity is the -OH molecule, which remains as a residue despite stringent manufacturing techniques. The -OH molecule has an absorption peak at 2.73 µm in the optical spectrum, which means that wavelengths near 2.73 µm have high attenuation. Correspondingly, the -OH molecule yields harmonics at 0.95 and 1.4 µm. As per the attenuation graph, the 1.4 µm peak is a severe hindrance to commercial optical communication [6].

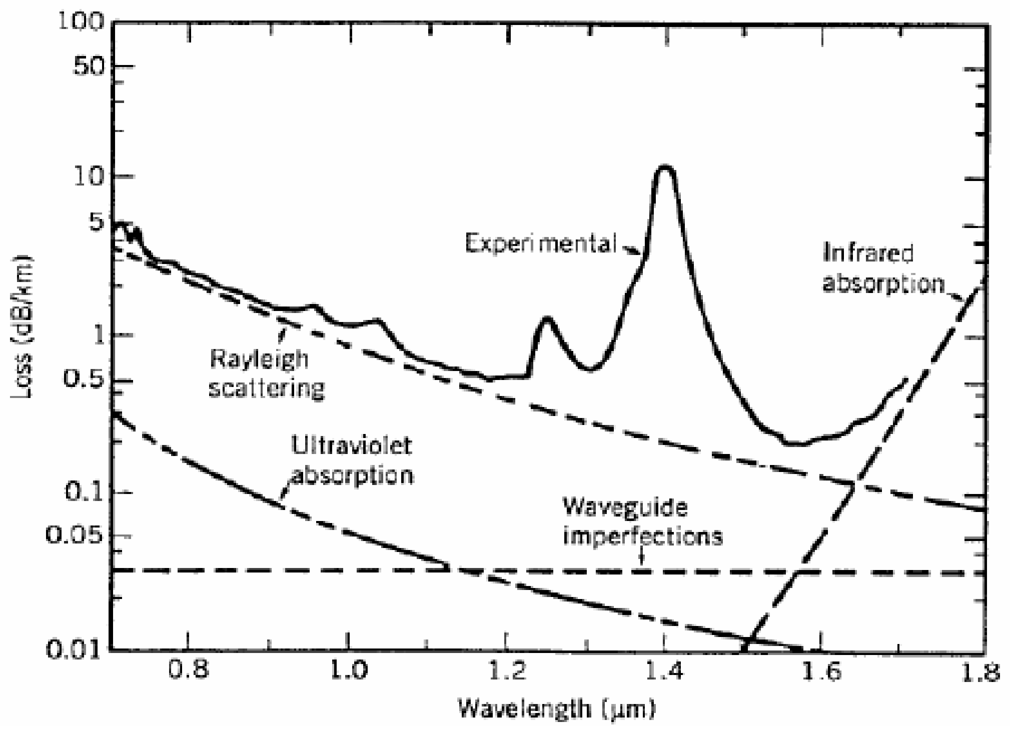


Figure 1.8: Optical fiber attenuation curve

7.3. Rayleigh Scattering:

Light scatters due to dense fluctuations in the core leading to a phenomenon known as Raleigh scattering. This phenomenon results from the collision of light quanta with silica molecules, causing scattering in more than one direction. Depending on the incident angle, some portion of the light propagates forward and the other part deviates out of the propagation path and escapes from the fiber core. The amount of Raleigh scattering a signal is subject to is inversely proportional to the fourth power of wavelength · Therefore, short wavelengths are scattered more than longer wavelengths. Any wavelength that is below 800 nm is unusable for optical communication because attenuation due to Raleigh scattering is high. At the same time, propagation above 1.7 µm is not possible due to high losses resulting from infrared absorption [6].

7.4. Bending Losses:

Bending of the fiber can be classified as micro bending and macro bending. Microlending is caused by imperfections in the cylindrical geometry of fiber during the manufacturing cycles. Macro bending is the result of bending of fiber in small radius (radius in order of cm). Each bending phenomenon causes attenuation in the fiber [6].

7.5. Waveguide Losses:

The losses that result from the waveguide structure arise from power leakage, bending, micro bending of the fiber axis, and defects and joints between fibers. The power leakage is significant only for depressed cladding fibers.

7.6. Joint Or Splice Loss:

Ultimately, the fibers will have to be spliced together to form the final transmission link. With fiber cable that averages 0.4–0.6 dB/km splice loss in excess of 0.2 dB/spliced rustically reduces the unrepeated distance that can be achieved. It is therefore extremely important that the fiber be designed so that splicing loss can be minimized. Splice loss is mainly due to the result of axial misalignment of the fiber core as shown in Figure 1-53[9].

8. Wavelength Division Multiplexing (WDM):

A single mode fibre can support many different wavelengths at the same time (see section A.3). If two different colored lasers (different wavelength, fibre chosen in a way that both are single mode) excite a mode in a fibre each and then both of them are multiplexed onto the same single mode fibre, the fibre has now two first order modes with different wavelengths travelling in it [5]. This is not to be confused with a multimode fibre, where every color has several different modes! The different channels are independent of each other [4]. The wavelength also serves another purpose: As it is unique for every channel, it can be seen as a kind of an address to route the signal. At the end of the fibre, the different wavelengths have to be separated from each other (demultiplexed) and then detected separately [5].

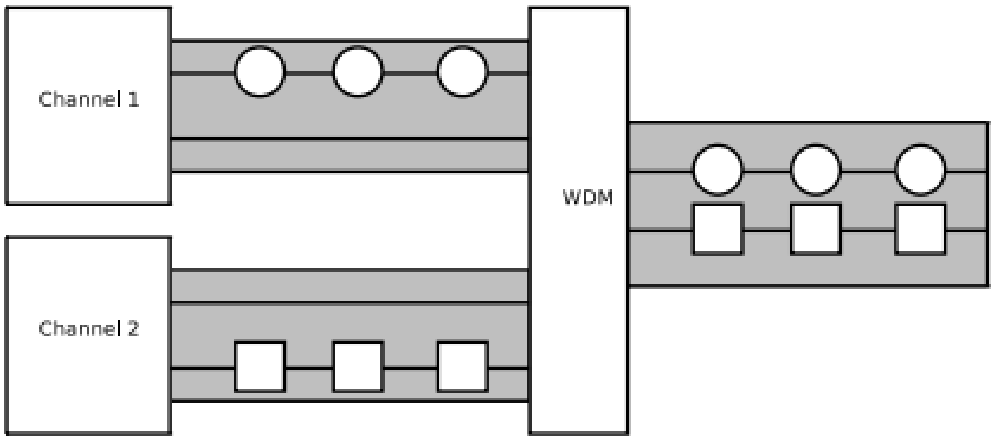


Figure 1.9: Simple schematic of a WDM system for N = 2

There are four basic approaches to multiplexing that each has a set of variations and implementations: Frequency Division Multiplexing (FDM), Wavelength Division Multiplexing (WDM), Time Division Multiplexing (TDM) and Code Division Multiplexing (CDM).

A WDM system uses a multiplexer at the transmitter to join the signal together and a demultiplexer at the receiver to split them apart. With the right type of fiber, it is possible to have a device that does both simultaneously and can function as an optical add-drop multiplexer.

- Advantages of WDM:

Wavelength division multiplexing has several advantages over the other presented approaches to increase the capacity of a link:

• Works with existing single mode communication fibre [10, 11].

• Works with low-speed equipment [10,11]

• Is transparent: Doesn't depend on the protocol that has to be transmitted [10, 12].

• Is scalable: Instead of switching to a new technology, a new channel can easily be added to existing channels. Companies only have to pay for the bandwidth they actually need [10, 12].

• It is easy for network providers to add additional capacity in a few days if customers need it. This gives companies using WDM an economical advantage. Parts of a fibre can be leased to a customer who then gets fast network access without having to share the connection with others. The telecommunication company on the other hand still has an independent part of the fibre available for other customers [10,12].

9.The Bit Error Rate and The Quality Factor:

Bit Error Rate, BER is used as an important parameter in characterising the performance of data channels. When transmitting data from one point to another, either over a radio/ wireless link or a wired telecommunications link, the key parameter is how many errors will appear in the data that appears at the remote end. As such Bit Error Rate, BER is applicable to everything from fibre optic links, to ADSL, Wi-Fi, cellular communications, IoT links and many more. Even though he data links may utilise very different types of technology, the basics of the assessment of the bit error rate are exactly the same.

BER is a unitless performance measure, often expressed a percentage, it is given by the following formula:

$$BER = \frac{\text{number of bit error}}{Total\ number\ of\ transmitted\ bits} \qquad (1.8)$$

The Quality Factor is a measure of how noisy a pulse is for diagnostic purposes. The eye pattern oscilloscope will typically generate a report that shows what the Q Factor number is. Q Factor is a key parameter that determines the performance of a communication channel. Q Factor represents SNR optical for binary / digital optical communication and facilitates system performance analysis [23].

The relationship between Quality factor and Bit Error Rate is:

$$BER = \frac{1}{2} erfc(\frac{Q}{\sqrt{2}}) \approx \frac{e^{\frac{-Q^2}{2}}}{\sqrt{2\pi}Q} \qquad (1.9)$$

Q: the quality factor

$$erfc = \frac{2}{\pi}\int_x^{\infty} e^{-t^2} dt \qquad (1.10)$$

As it’s seen the bigger the Q factor the smaller the BER [22].

CHAPTER 2:

DISPERSION

IN OPTICAL FIBER AND

COMPENSATION

1. Introduction:

Nowadays, with high growth of internet a need of a high capacity of network systems is felt. Demand for higher bandwidth and capacity have become much more challenging factor for a service provider. In these conditions optical communication is most favourable medium for delivering data to the user with excellent bandwidth and transmission performance among the existing communication techniques.

An optical transmission system suffers from an inherent problem of dispersion. This is the main concern for an optical communication network [13]. Dispersions of transmitted optical signal cause distortion for both digital as well as analog signal. Dispersion in the fiber is one of the limiting factors to decide how much data can be sent along alive. Single Mode Fiber use in the high-speed fiber communication network suffers from the dispersion type known as chromatic dispersion. The Chromatic dispersion has a wavelength dependant nature.

The Erbium dope fiber amplifier (EDFA), is considered as a better candidate for high data rate transmission. EDFA works on 1550nm wavelength, at that wavelength Single Mode Fiber (SMF) dispersion measured is nearly about 15-20ps/(nm.km-1) [14]. So, it shows that dispersion is the main problem of long-distance communication. Also, when optical network moves from 2.5Gbps to 10Gbps and onward the acceptable tolerance of dispersion is drastically reduced. Dispersion is reduced by the factor of 16 when moving 2.5Gbps to 10Gbps and by and an additional factor of 16 moving from 10Gbps to 40Gbps [15].

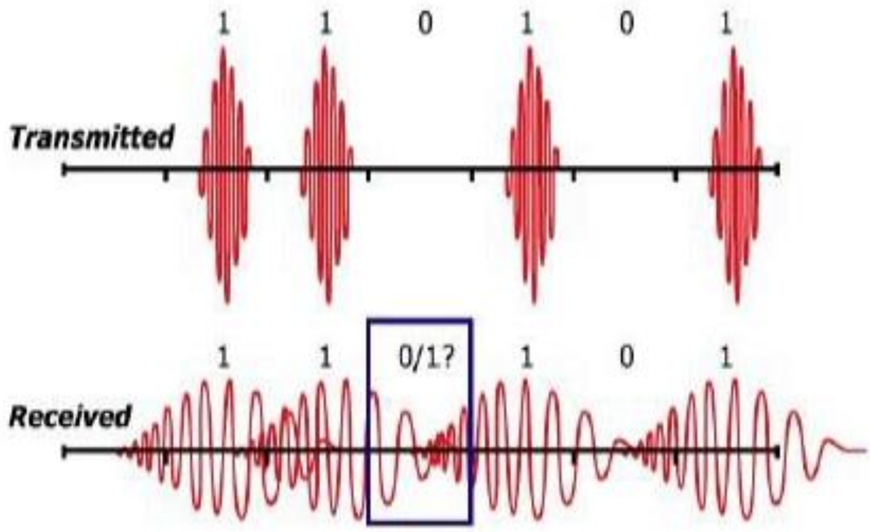


Figure 2.1 : Dispersion

Dispersion is generally divided into three categories: modal dispersion, chromatic dispersion and polarization mode dispersion.

2. Modal Dispersion:

In multi-mode fiber, deferent mode travel at deferent velocities, if a pulse is constituted from different modes, then internode dispersion occurs. We call this type of dispersion as intermodal dispersion, or modal dispersion. Modal dispersion limits the bandwidth of multimode fibers. the more modes are the greater the modal dispersion is. Typical bandwidth of step index fiber may be as low as 10 MHz over 1 km. modal dispersion may be considerably reduced, but ever complitely eliminated by the use of a core having a graded index fibers having bandwidth exceeding 3.5 GHz/km at 850 nm are commonly manufactured for use in 10 Gbps data link.

3. Chromatic dispersion:

3.1Material Dispersion:

Material dispersion comes from a frequency-dependent response of a material to waves. For example, material dispersion leads to undesired Chromatic aberration in a lens or the separation of colors in a prism. Material dispersion is not helpful in optical communications that it limits how much data can be sent, as the pulses will overlap and information will be lost.

3.2. Waveguide dispersion:

Waveguide dispersion is caused by the wavelength dependence of the group velocity due to specific fiber geometry. Waveguide dispersion is important in waveguides with small effective mode areas. But for fibers with large mode areas, waveguide dispersion is normally negligible, and material dispersion is dominant.

4. Polarization Mode Dispersion:

Polarization mode dispersion (PMD) is a special form of modal dispersion. This phenomenon describes a situation in which the electromagnetic wave components that make up an optical signal travel at different speeds within the fiber. This causes a multipath interference at the receiver. PMD is difficult to predict and may possibly vary with temperature and environment, the twisting of the cable as it was pulled, and even between production runs from the same manufacturer.

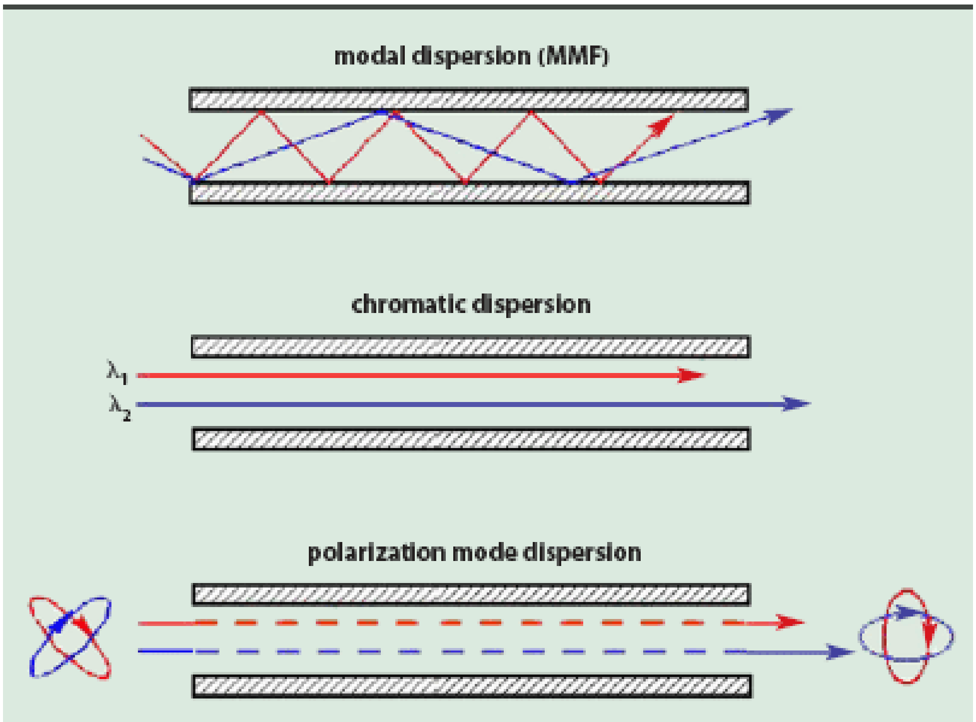


Figure 2.2: The three types of optical dispersion

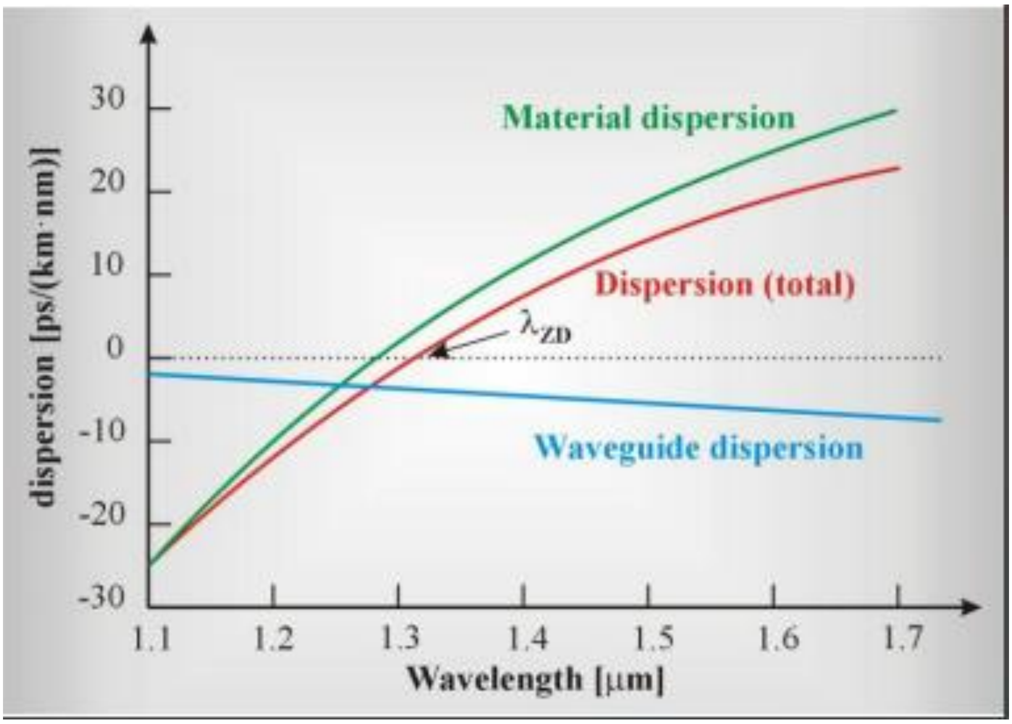


Figure2.3: Total dispersion, material dispersion and the waveguide dispersion in a typical single mode fiber.

5. Dispersion Compensation Technologies:

In order to remove the broadening or the spreading of the light pulses, dispersion compensation is the most important feature required in optical communication systems, there are many techniques that can be used. Each of them has its own advantages and disadvantages. The most commonly implemented techniques in practical situation are discussed in detail:

5.1. Fiber Bragg Grating (FBG):

Bragg gratings are cyclic periodic perturbations of the refractive index in the fiber. For an incident WDM composite signal propagating through this perturbation of refractive index, one wavelength of the entire propagating spectra would be reflected back (backward). This wavelength is known as Bragg's wavelength

$$\lambda_B = 2nt \qquad (2.1)$$

where n is the refractive index of the waveguide and t are the period of perturbation or grating. Therefore, when a composite WDM signal is incident on a Bragg's grating, all wavelengths except Bragg's wavelength pass through while Bragg's wavelength is reflected back.

Gratings can be "written" onto a fiber in numerous ways. One popular method is to use photosensitivity of doped Germanium in fiber and etch a grating pattern by exposing the photosensitive fiber to alternating intensities of ultraviolet light. The FBG can be characterized by low loss 0.1 dB and low channel cross-talk. FBGs find applications in most WDM systems, such as channel drop elements, dispersion compensation devices, and filters.

5.2. Digital Filters:

C.H. Cheng, G. Lenz, C.K. Madsen, J.A. Walker, J.E. Ford, K.W. Goossen, T.N. Nielsen, A.J. Bruce, M.A. Cappuzzo, L.T. Gomez, R.E. Scoti [16], [17], [18], [19] implemented digital signal processing in order to compensate chromatic dispersion. The use of All Pass Optical Filter to compensate dispersion is the most effective way of dispersion compensation using digital filters. Optical all pass filters are lossless filters that are capable of tuning a desired phase response by manipulating the number of stages keeping magnitude response of the system constant. The free spectral range (FSR) of all pass optical filters is about 100 GHz and has a very minute polarization dependency of range +100 ps/km to -100 ps/km, with a 50 GHz passband width and group delay ripple value of less than 3 ps peak.

5.3. Dispersion Compensating Fiber (DCF):

In dispersion compensating fiber technique we use a fiber having a large negative dispersion along with a standard fiber. The amount of light dispersed by a normal fiber in reduced or even nullified by using a dispersion compensating fiber having a very large value of dispersion of opposite sign as compared to that of standard fiber [21]. There are basically three schemes that can be used to install a dispersion compensating fiber-pre, post or symmetrical. In pre compensation technique DCF is inserted in the loop before the standard mode fiber as shown in figure 2.4. In post compensation technique the DCF is inserted in the loop after the standard fiber as depicted in figure no2.5. In symmetrical compensation DCF is inserted both before and after the standard mode fiber as shown in figure 2.6. out of these three schemes symmetrical compensation shows a better performance in compensating dispersion.

The length of DCF can be calculated by:

$$D_{SMF} \,.\, L_{SMF} = -D_{DCF} \,.\, L_{DCF} \qquad (2.2)$$

D_{SMF}, D_{DCF}: are dispersion factors of single mode fiber and DCF respectively

L_{SMF}, L_{DCF}: are lengths of single mode fiber and DCF respectively

The positive dispersion of standard mode fiber in C and L band (check appendix B) can be compensated by using dispersion compensating fiber having high values of negative dispersion -70 to -90 ps/nm.km [20].

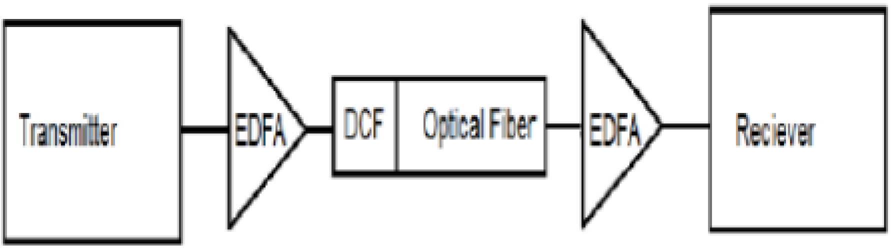


Figure 2.4: pre compensation DCF

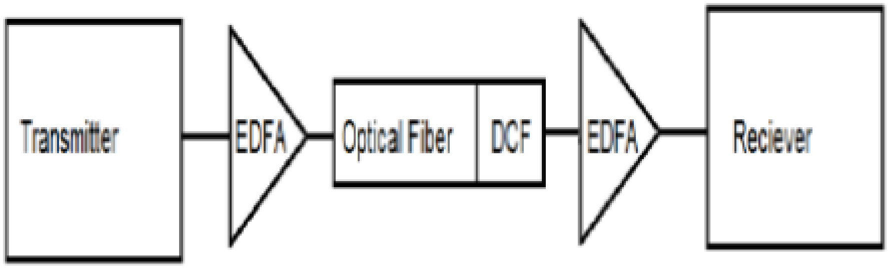


Figure 2.5: post compensation DCF

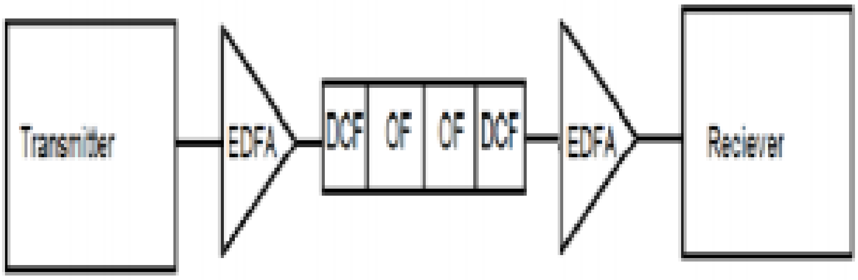


Figure 2.6: symmetrical compensation DCF

CHAPTER 3:

SIMULATION

AND

RESULTS

1. Introduction:

In this chapter we present the simulation results of the dispersion compensation using DCF with three types of configuration (Pre, post and symmetric), then we compare between them based on the bit error rate (BER) and the quality factor (Q factor) at various bit error rates (2.5 Gbps,5Gbps,7.5Gbps,10Gbps and 12.5Gbps). After selecting the best configuration, we divide the WDM system into multiple stages with deferent lengths and deferent channels number (4 channel, 8 channel and 16 channel) and perform the same comparison.

2. OptiSystem Software and Its Application:

OptiSystem is an innovative optical communication system simulation package that designs, tests, and optimizes virtually any type of optical link in the physical layer of a broad spectrum of optical networks, from analog video broadcasting systems to intercontinental backbones. OptiSystem is a stand-alone product that does not rely on other simulation frameworks. It is a system level simulator based on the realistic modelling of fiber-optic communication systems. It possesses a powerful new simulation environment and a truly hierarchical definition of components and systems. Its capabilities can be extended easily with the addition of user components, and can be seamlessly interfaced to a wide range of tools.

OptiSystem allows for the design automation of virtually any type of optical link in the physical layer, and the analysis of a broad spectrum of optical networks, from long-haul systems to MANs and LANs. OptiSystem's wide range of applications include:

• Optical communication system design from component to system level at the physical layer.

• CATV or TDM/WDM network design.

• Passive optical networks (PON) based FTTx.

• Free space optic (FSO) systems.

• Radio over fiber (ROF) systems.

• SONET/SDH ring design.

• Transmitter, channel, amplifier, and receiver design.

• Dispersion map design.

• Estimation of BER and system penalties with different receiver models.

• Amplified system BER and link budget calculations.

3. Simulation Setup:

Here for designing 4 channel WDM, we have used optisystem 7.0 software The setup has 3 sections, they are transmitter section, medium for transmission and receiver section.

The transmitter section consists of pseudo random bit sequence generator, NRZ pulse generator, CW laser and Mach-Zehnder modulator. The pseudo random bit sequence generator has a bit rate of 2.5 (as a start) Gbps for generation of pulses. NRZ pulse generator is used for line coding. CW laser having power= 10dbm is used and frequency at each channel vary from 193.1 to 193.4 THz followed by Mach-Zehnder modulator.

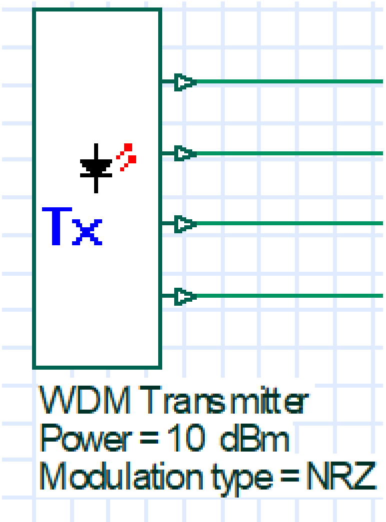


Figure 3.1: transmitter model

Then the transmitted signal is passed through a MUX having 4x1 channel and after getting multiplexed the signal is passed through a transmitting medium. The medium consists of DCF, optical fiber, amplifiers (EDFA) to amplify the signal and also to overcome the attenuation whenever required. After passing the signal through the medium it is again passed through the WDM DEMUX where demultiplexing takes place.

Basically there are three configurations of DCF as follows: -Pre compensation: It is defined as when the DCF is placed at the initial point of optical link and before the SMF. - Post compensation: It is defined as the condition when DCF is placed at the last point of optical link after SMF. - Symmetric compensation: two DCFs are placed at the transmitter and receiver ends, and the SMF between them.

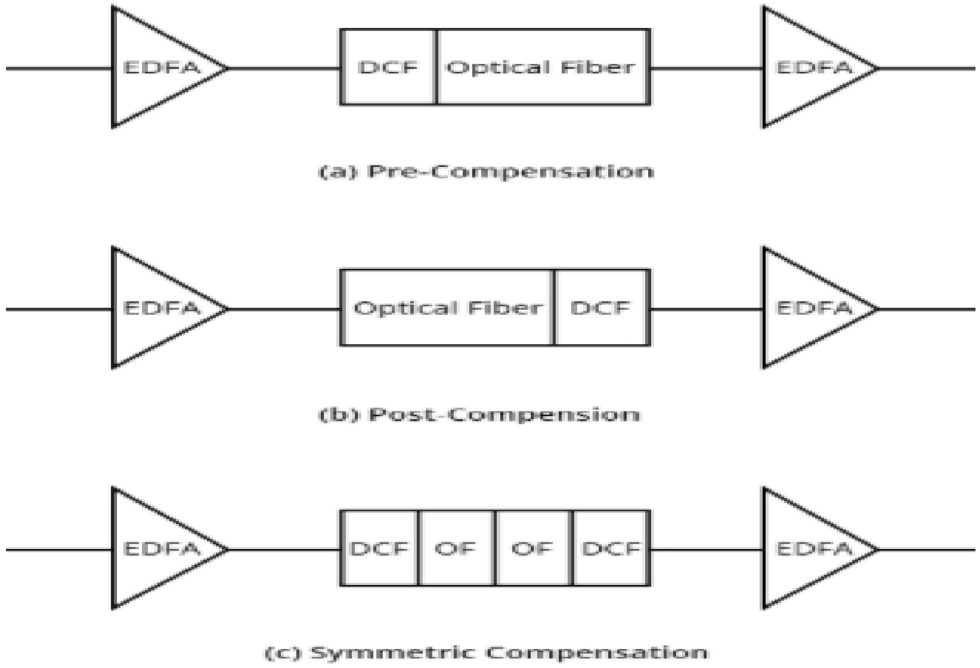


Figure 3.2: transmission line model: a-pre-compensation, b-post-compensation, c- symmetric compensation

The last section is the receiver section which consists of optical receiver and BER analyzer. By the help of BER analyzer we can get the graph of the whole setup.

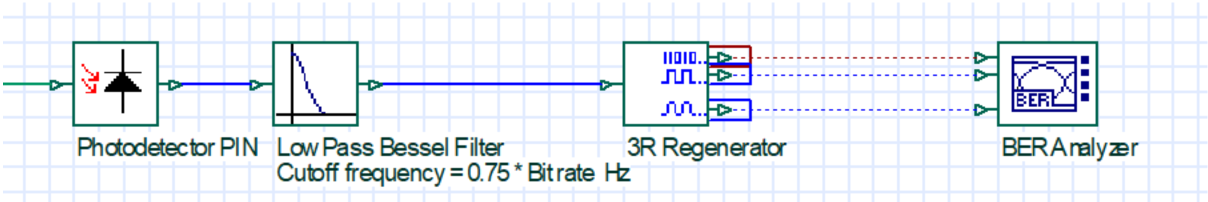


Figure 3.3: receiver model

3.1. Parameters of The System:

Table 3.1: The parameters of our system

Parameter	Value
Bite rate (Gbps)	2.5 5 7.5 10 12.5
Laser power (dbm)	10
Length of SMF (km)	100 50-50 25-75 75-25 30-40-30 25-25-25-25
Length of DCF(km)	20 10 5 8 6 (according to equation 2.2)

Dispersion coefficient of SMF(ps/nm/km)	16.75
Dispersion coefficient of DCF(ps/nm/km)	-83.75
EDFA gain(db)	6
SMF attenuation(db/km)	0.2
DCF attenuation(db/km)	0.265
Dispersion slope of SMF(ps/nm^2/km)	0.075
Dispersion slope of DCF(ps/nm^2/km)	-0.075

First step: the system is simulated without dispersion compensation at 10Gbps as shown in figure 3.4:

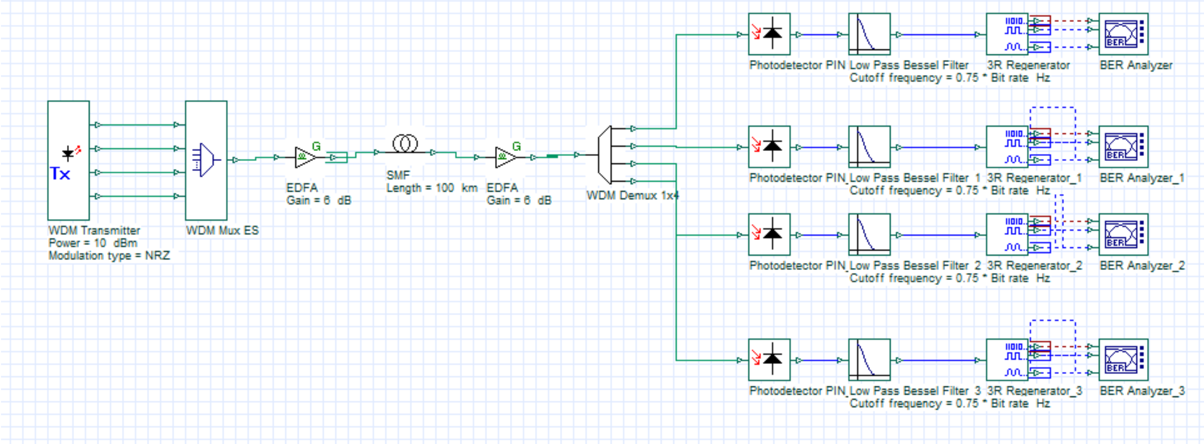


Figure 3.4: 4-channel WDM system

The result in channel one is demonstrated in the following eye diagram (figure 3.5) (check appendix A)

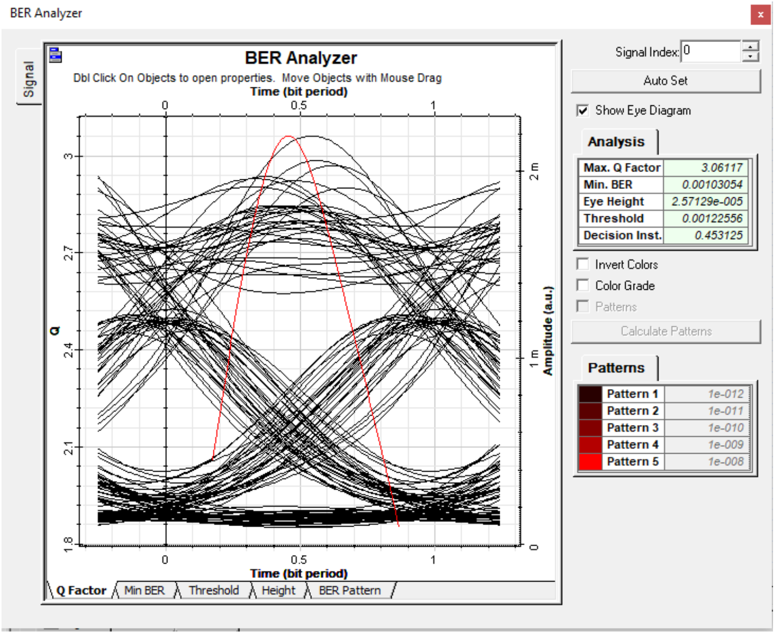
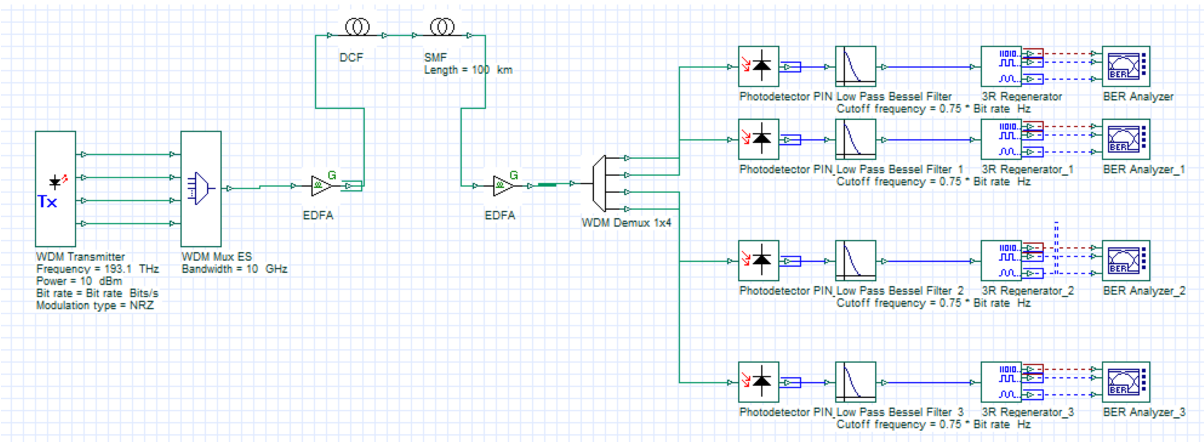


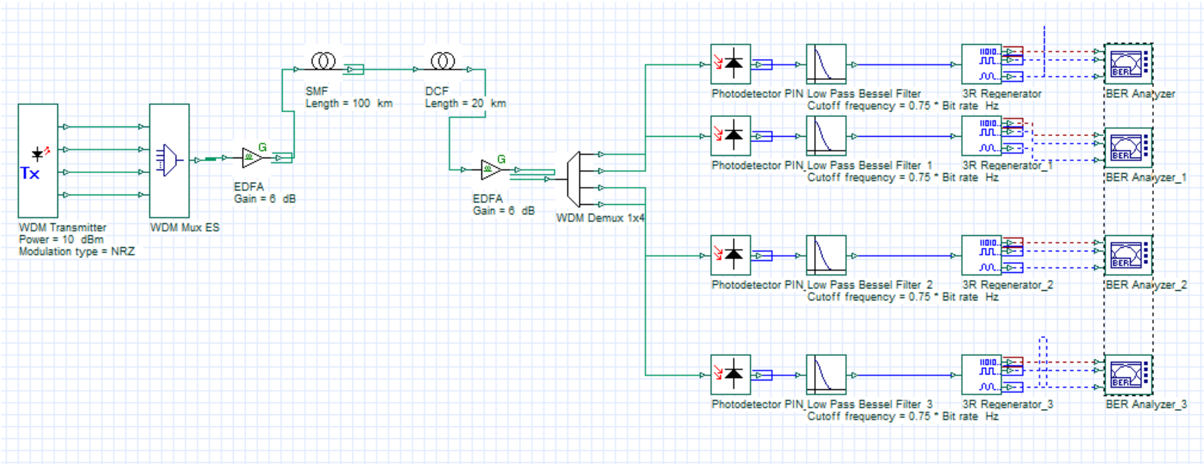
Figure 3.5: eye diagram of channel 1 in 4-channel WDM

As it is observed in the last figure the uncompensated system has some interference between codes, low Q factor and noticeably high BER and unclear eye diagram.

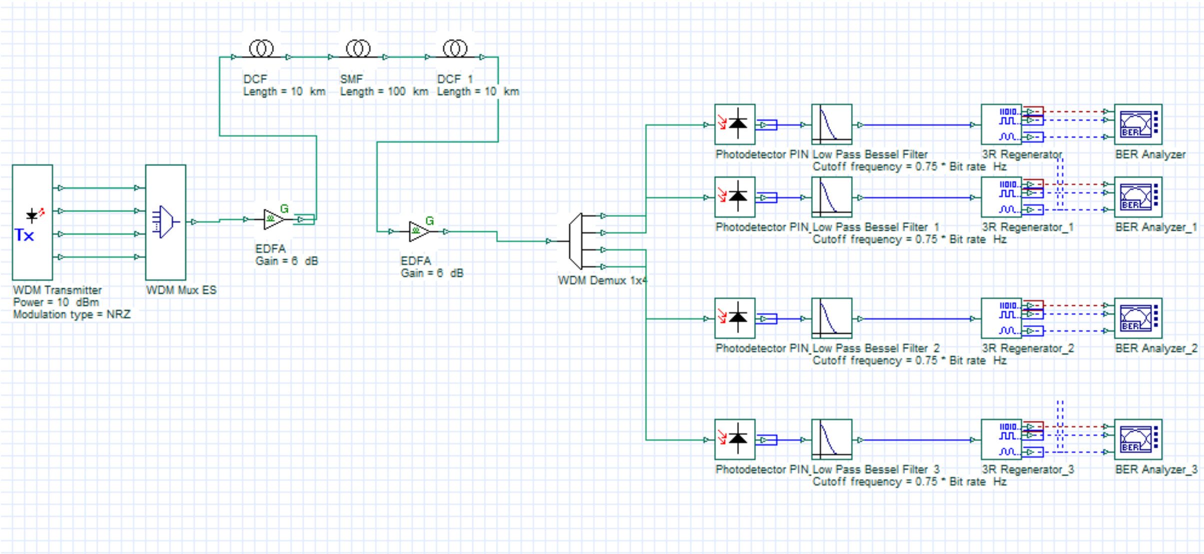
Second step: A DCF is added to the system with its three configurations:



(a)



(b)

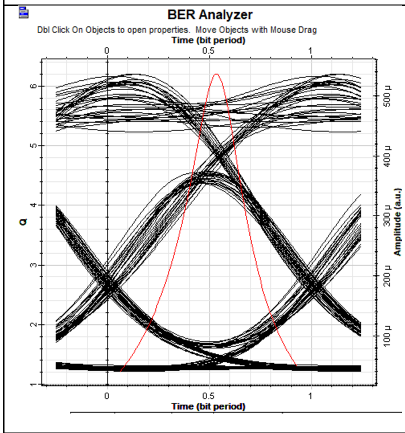
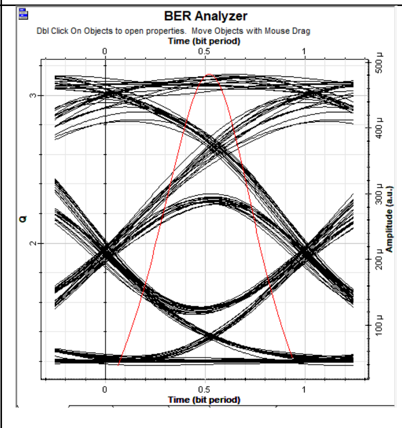
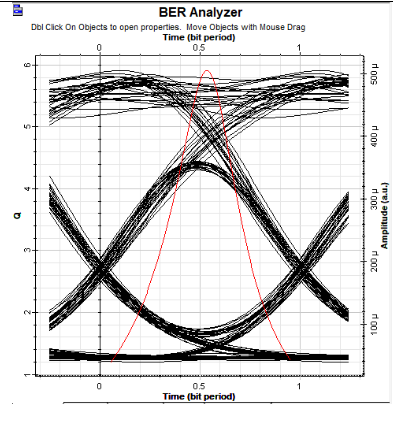


(c)

Figure 3.6: 4-channel WDM with: a-pre-compensation, b-post-compensation, c-symmetric compensation

The obtained results are shown in table 3.2

Table 3.2 :4-channel WDM with DCF results

Pre-compensation		Post-compensation		Symmetrical -compensation	
					
BER	Q	BER	Q	BER	Q
2.5416 e^{-10}	6.19736	7.79791 e^{-4}	3.14134	1.52458e^{-9}	5.90865

In table 3.2, we can see that, BER of the pre method is 2.5416 e^{-10} means that it is better than other symmetric and post compensation method, If BER of system is less then, probability of error of bit loss during transmission is less and data transmission for long distance is achieved easily. Also Q factor of pre system is 6.19736, pre-compensation method gives better result than other methods of compensation under the same parameters.

Third step: By selecting the best configuration (pre-compensation) based on the previous results we set a simulation with different data rate (2.5, 5, 7.5, 10 and 12.5Gbps) and dividing the length of SMF and DCF into stages as shown is table 3.1 and then we try to increase the number of channels.

A. Simulation of Pre-DCF Technique Using Multistage in 4-channels WDM:

We simulate our system with different configurations of DCF and SMF lengths and we increment the bit rate as it is represented in the following figures:

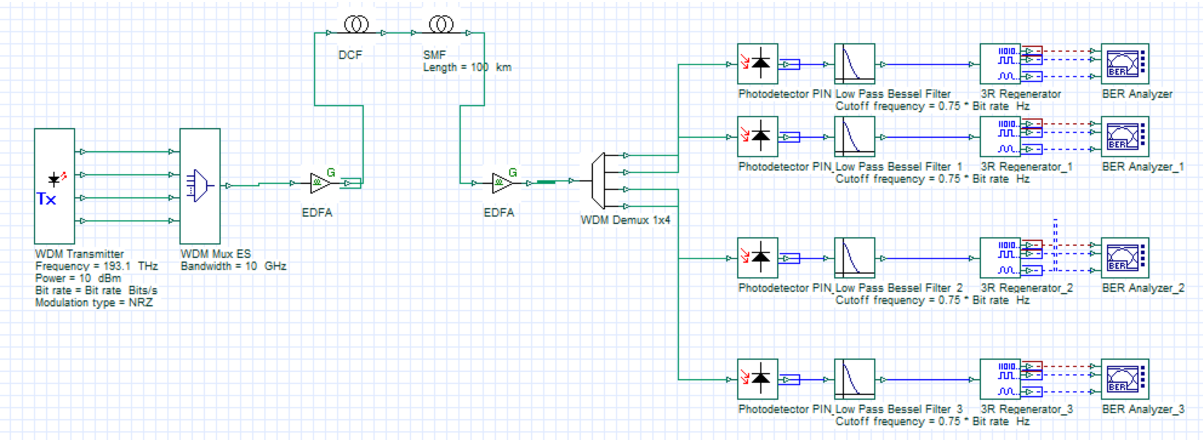


Figure 3.7: 4-channel WDM with 100km SMF

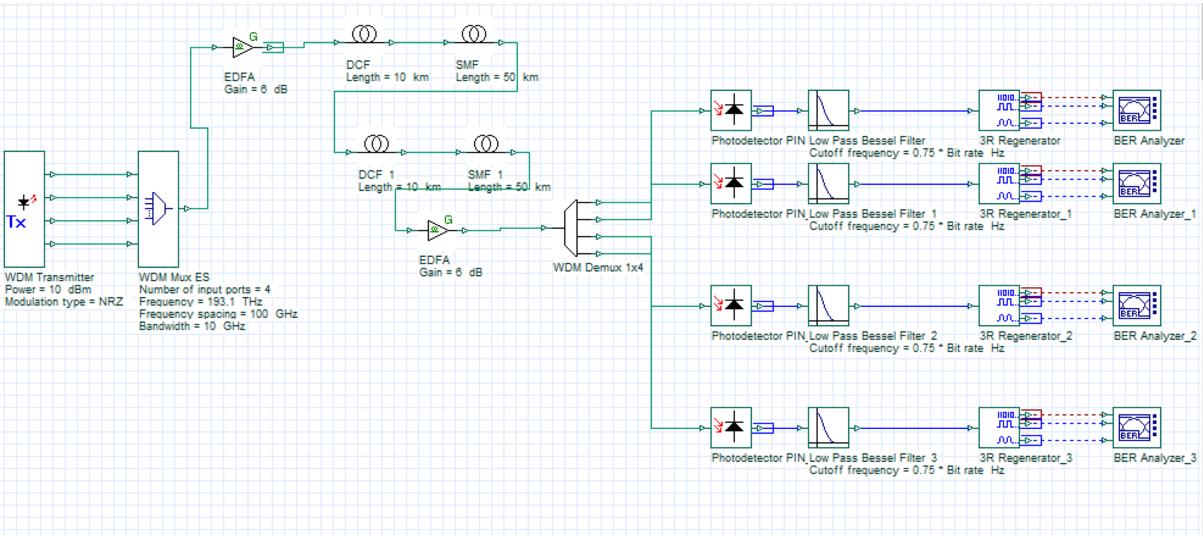


Figure 3.8: 4-channel WDM with 50-50km SMF

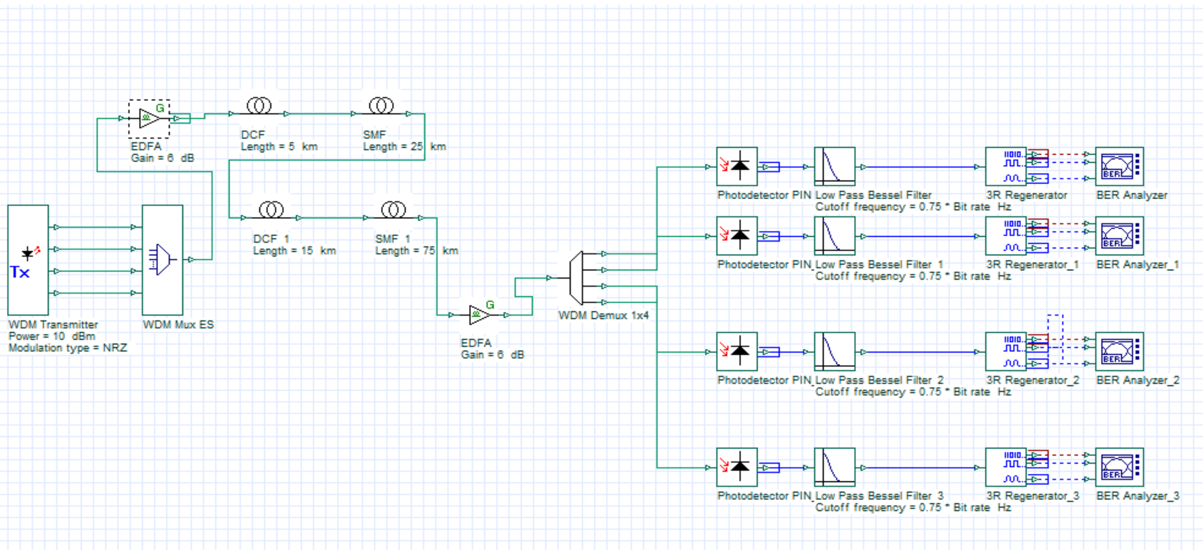


Figure 3.9: 4-channel WDM with 25-75km SMF

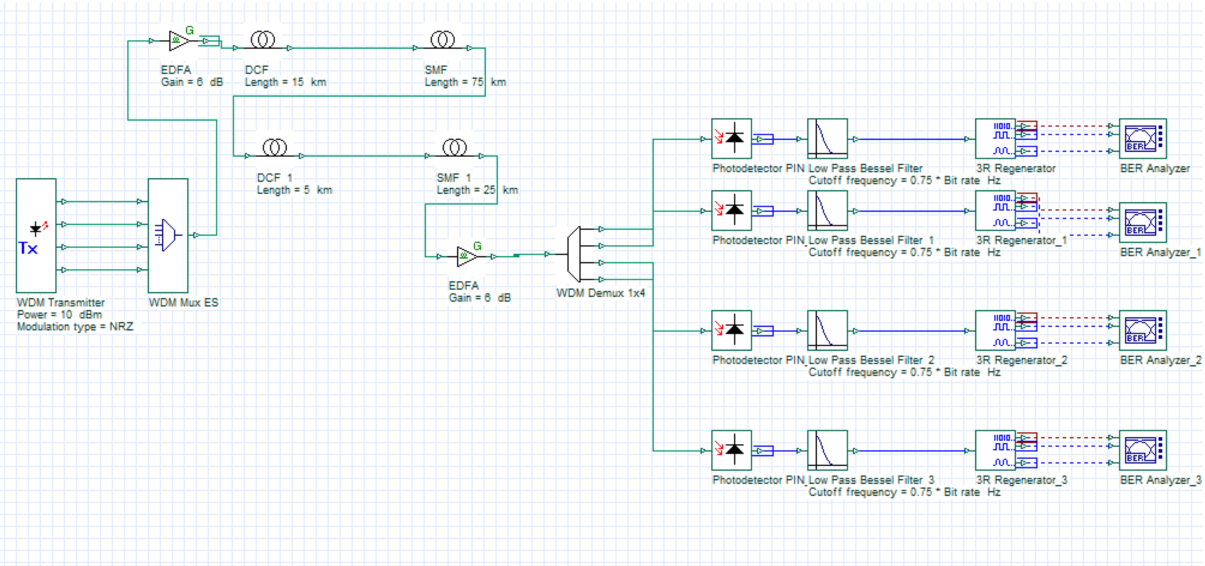


Figure 3.10: 4-channel WDM with 75-25km SMF

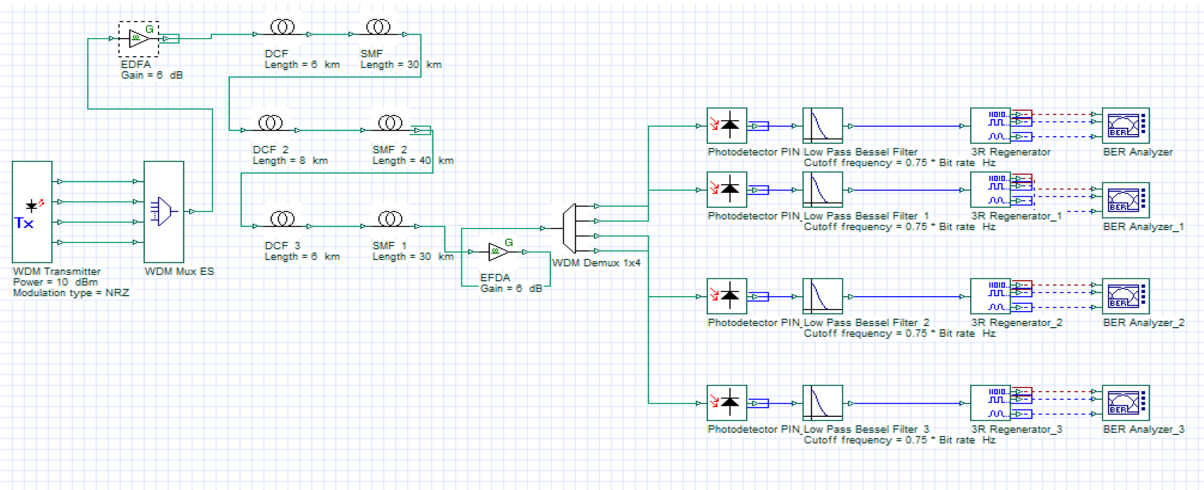


Figure 3.11: 4-channel WDM with 30-40-30km SMF

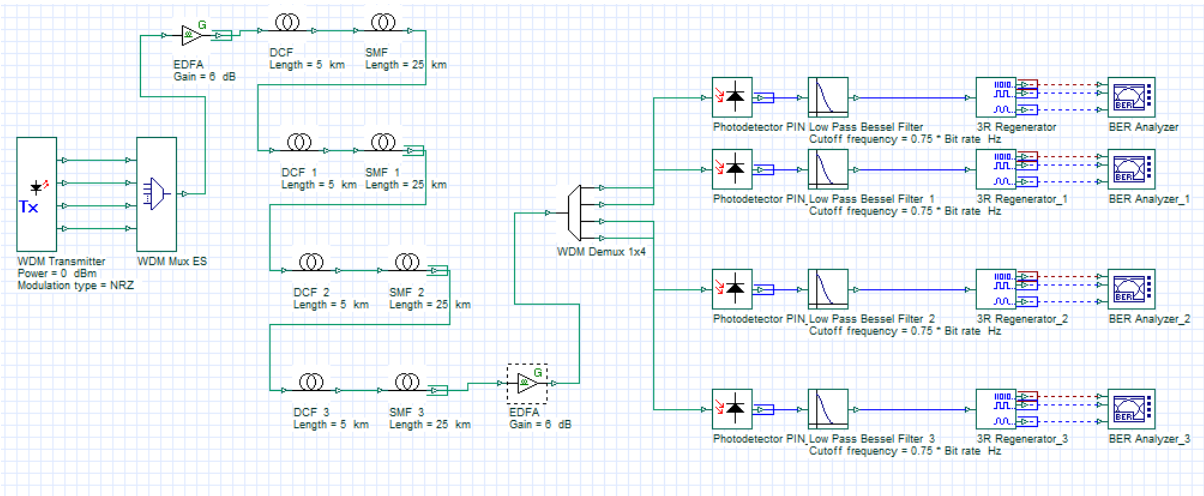


Figure 3.12: 4-channel WDM with 25-25-25-25km SMF

The simulation gives us the results demonstrated in table 3.3:

Table 3.3:4-channel WDM results of different SMF length and Bit rates (channel 1)

SMF (km) / Bit Rate (gbps)	100		50-50		25-75		75-25		30-40-30		25-25-25-25	
	Q	BER	Q	BER	Q	BER	Q	BER	Q	BER	Q	BER
2.5	54.16	0	6.2543	1.75e-10	52.93	0	53.41	0	48.86	0	30.0891	0
5	38.65	0	30.1296	0	36.74	0	60.65	0	37.22	0	28.0027	0
7.5	19.669	5.82e-85	14.35	4.51e-47	12.15	2.27e-34	17.18	1.51e-66	12.02	1.13e-33	10.7564	2.4e-27
10	6.19736	2.52e-10	6.2543	1.75e-10	5.47	1.88e-8	6.52	2.92e-11	5.63	7.9e-9	5.2458	6.8326e-8
12.5	4.0152	2.96e-5	3.8953	4.9e-5	3.3	0.0004	4.03	2.69e-5	3.45	0.0002	3.3173	0.00041

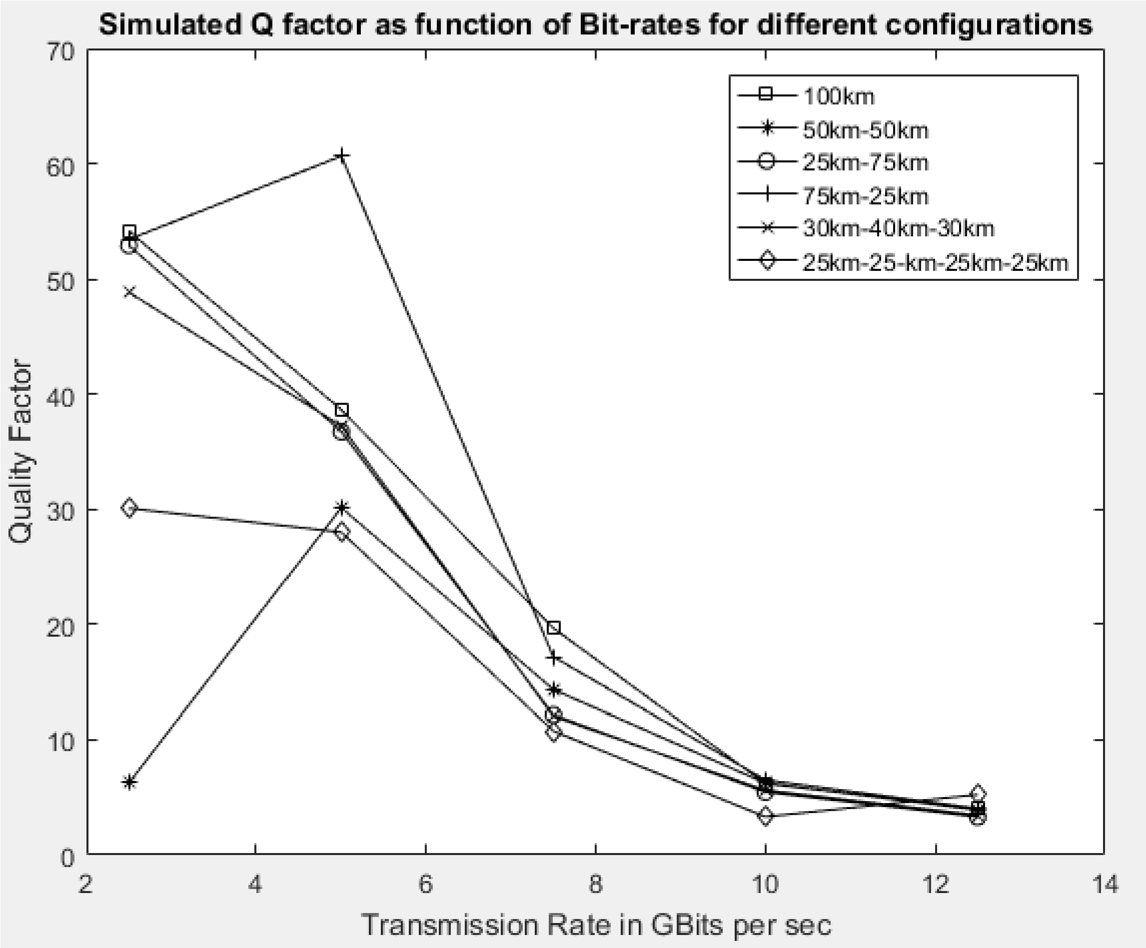


Figure 3.13 : Simulated Q factor as function f Bit-rates for different configurations

As it is observed on the previous table, whenever we increase data rate a lower Q factor and a higher BER are obtained. At 2.5 and 5 Gbps the results are almost perfect with a remarkable high Q factor and almost a nihilistic BER for all configurations. At higher bit rates the difference of results between configurations started to be noticeable, its remarkable, hence 100 km and 75-25 km configurations give us better results and maximum reachable bit rate with acceptable Q factor and BER.

B. Simulation of Pre-DCF Technique Using Multistage in 8-channels WDM:

Based on the previous results we set our 8 channel WDM simulation using the 100 and the 75-25 km configuration.

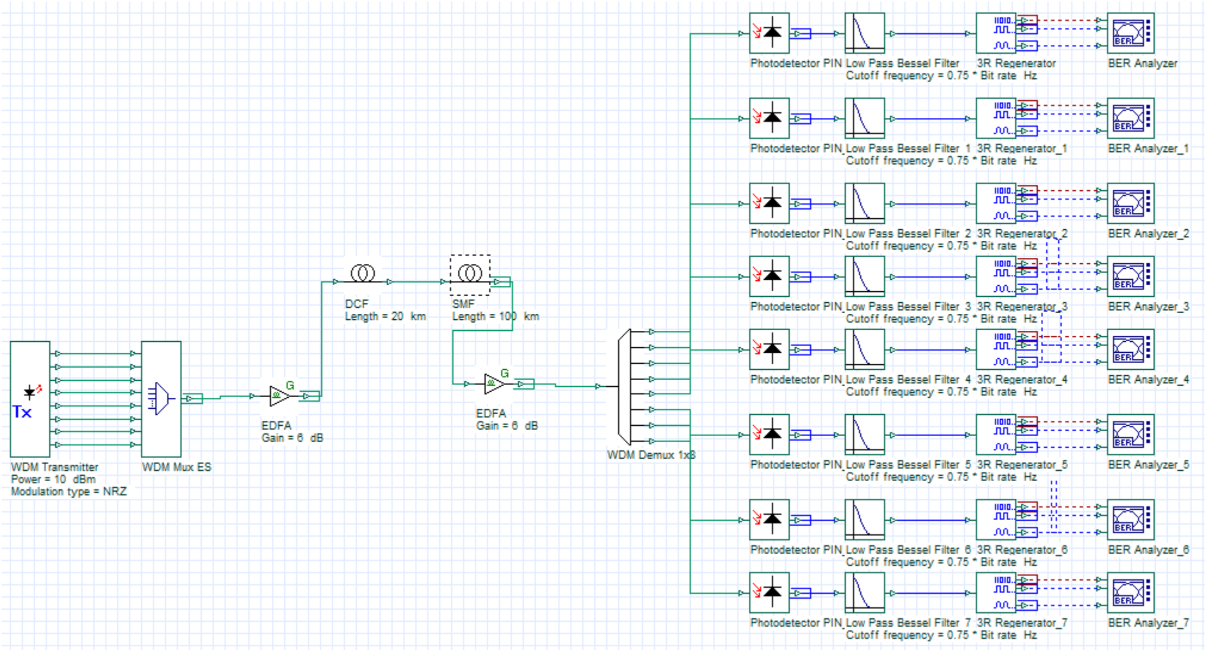


Figure 3.14: 8-channel WDM with 100 km SMF

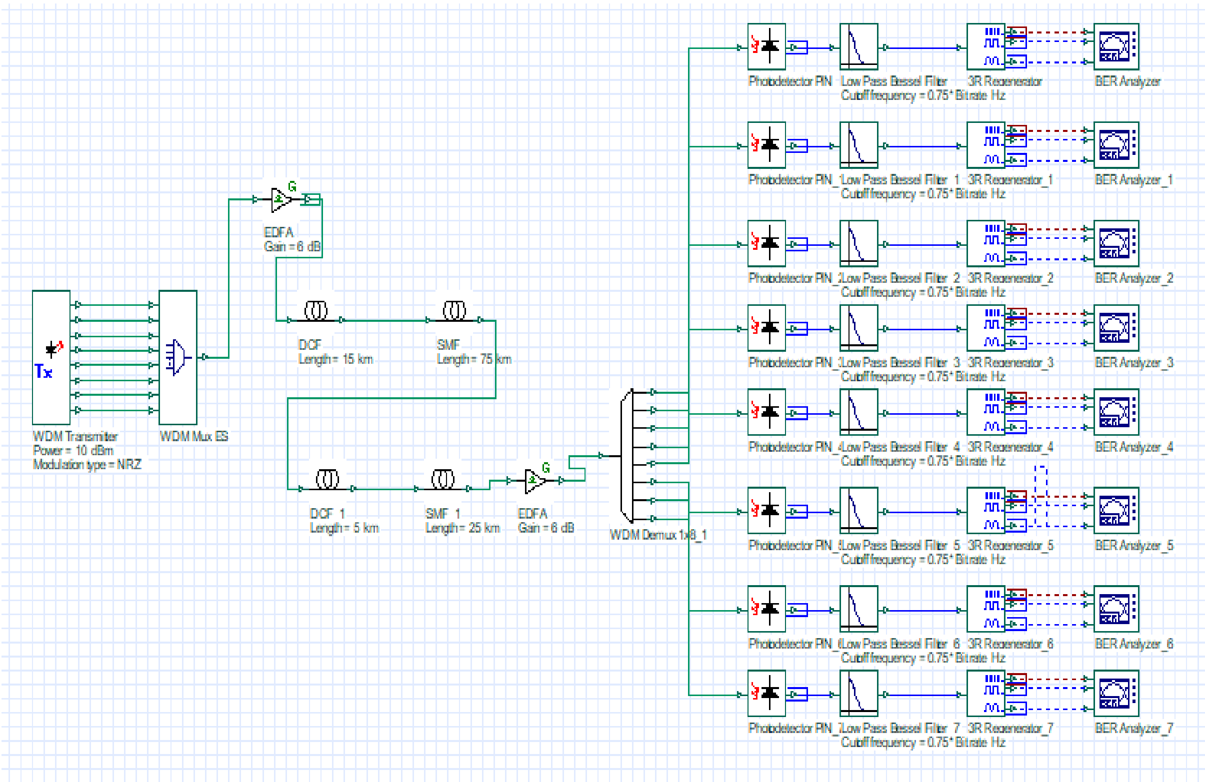


Figure 3.15 : 8channel WDM with 75-25 km SMF

We select three channel (ch1 ch5 ch8) and the obtained results are summarized in the following tables:

Table 3.4: 8-channel WDM results 100km SMF

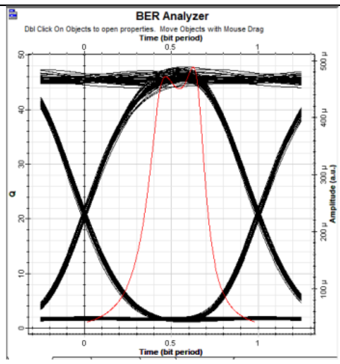
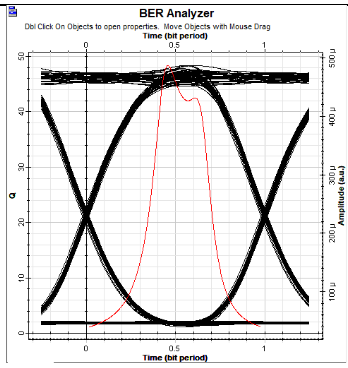
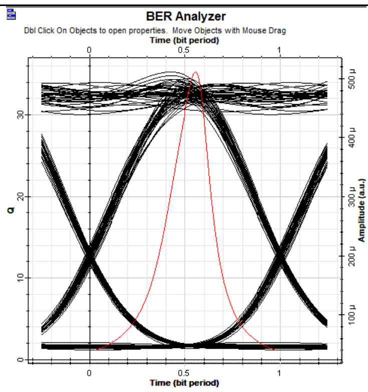
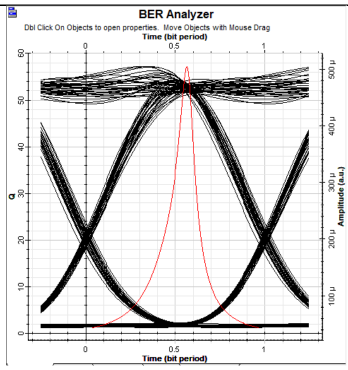
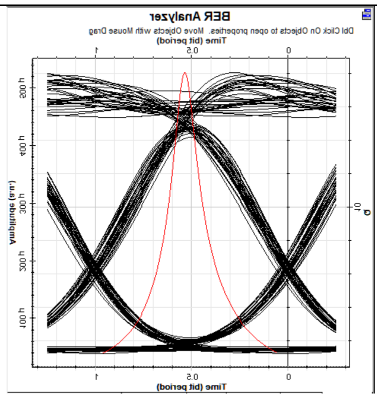
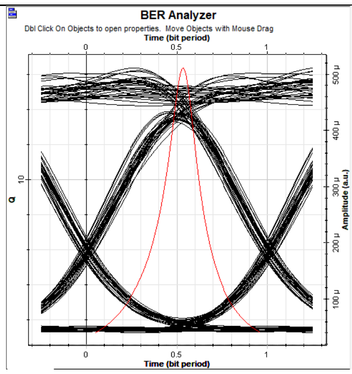
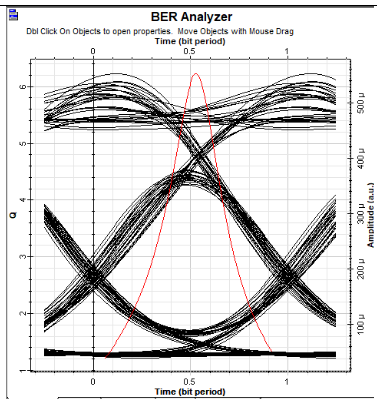
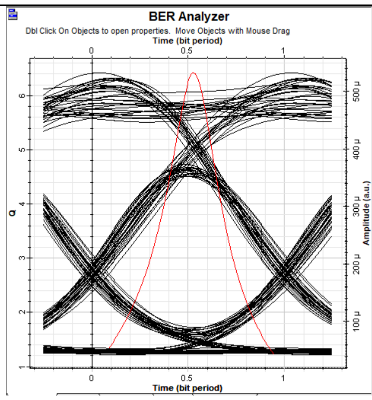
Bit rate (Gbps)	CH1		CH5		CH8	
	Q	BER	Q	BER	Q	BER
2.5	47.7804	0	37.4342	0	43.6977	0
5	35.2693	0	26.9158	0	35.891	0
7.5	18.0645	2.68e-73	13.9861	7.83e-45	16.8042	9.79e-64
10	6.2258	2.13e-10	5.7997	2.82e-9	5.9410	1.24e-9
12.5	3.9983	3.18e-5	3.6508	0.00013	3.8916	4.97e-5

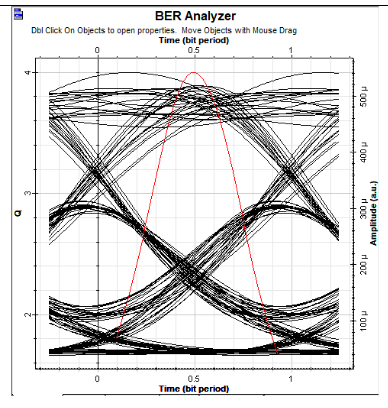
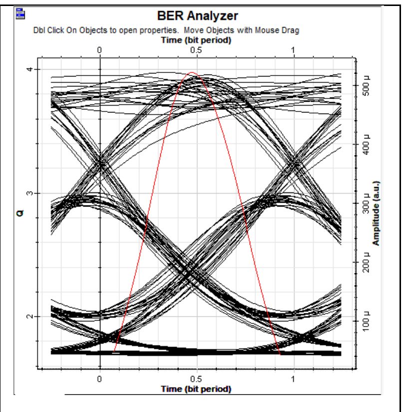
Table 3.5: 8-channel WDM results 75-25 km SMF

Bit rate (Gbps)	CH1		CH5		CH8	
	Q	BER	Q	BER	Q	BER
2.5	48.353	0	33..3951	0	47.6798	0
5	57.1907	0	31.5606	0	42.202	0
7.5	16.3616	1.58 e-60	15.1588	2.86 e-52	16.1168	8.53 e-59
10	6.1490	5.95 e-11	5.3999	2.67 e-8	6.2898	1.40 e-10
12.5	3.9754	3.51 e-5	3.6592	0.00012	3.8837	5.14 e-5

Here are the resulting eye diagrams in channel 1 for both configurations in table 3.6

Table 3.6: 8-channel WDM eye diagrams (ch1)

Bite rate (Gbps)	100km	75-25 km
2.5		
5		
7.5		
10		

12.5		

From tables 3.4, 3,5 and 3.6, in channel 1 and channel 8 the 75-25 km configuration gives better results for 2.5Gbps and 5Gbps we have got higher Q factor and wider eye diagrams but as a higher data rate is transferred, the 100 km configuration Seems more convenient for the same channels. In the other side, the results obtained in channel 5, for 2.5 Gbps and 5 Gbps the 100 km configuration are slightly better and vice versa for the other bit rates.

C. Simulation of Pre-DCF Technique Using Multistage in 16-channels WDM:

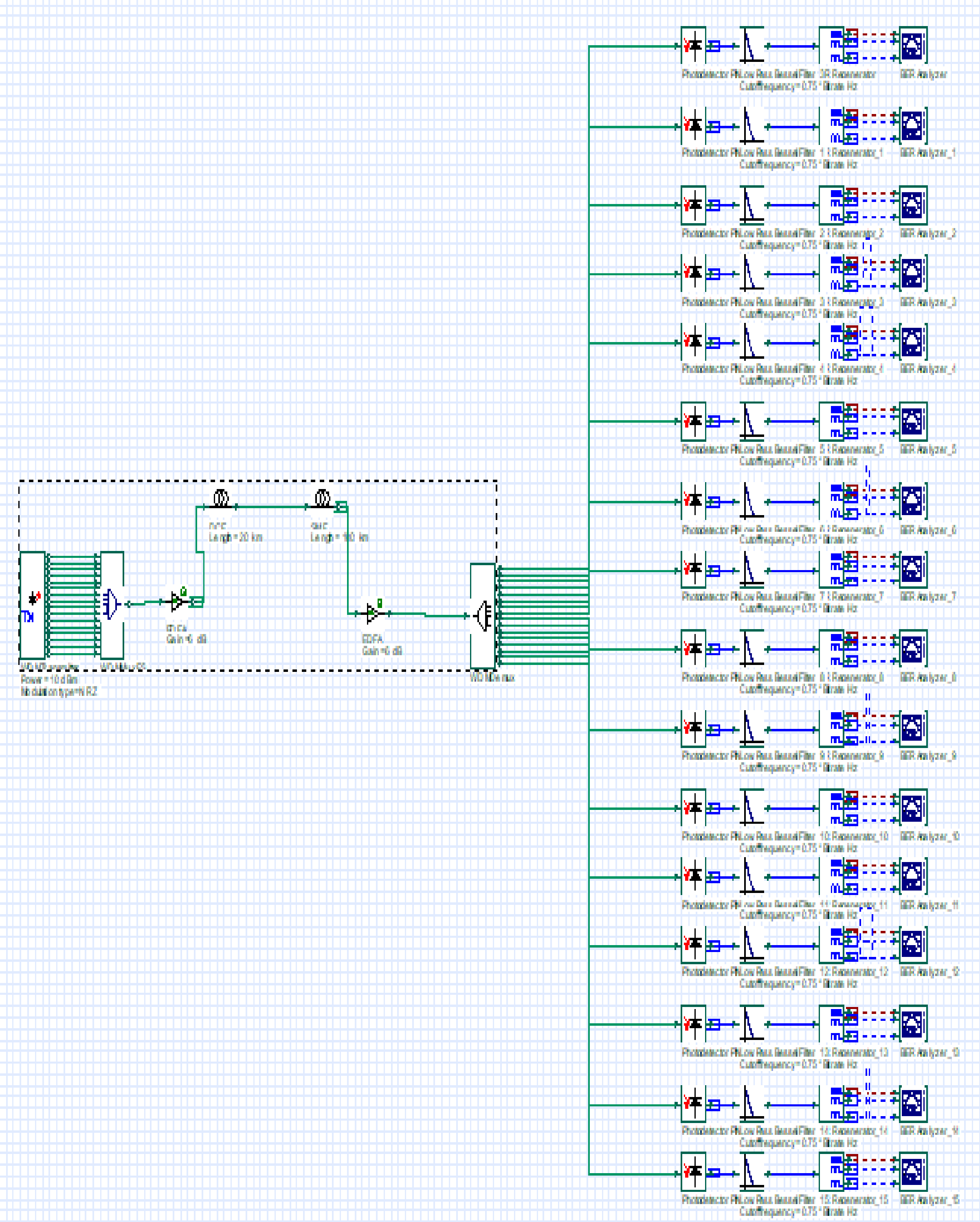


Figure 3.16: 16-channel WDM with 100 km SMF

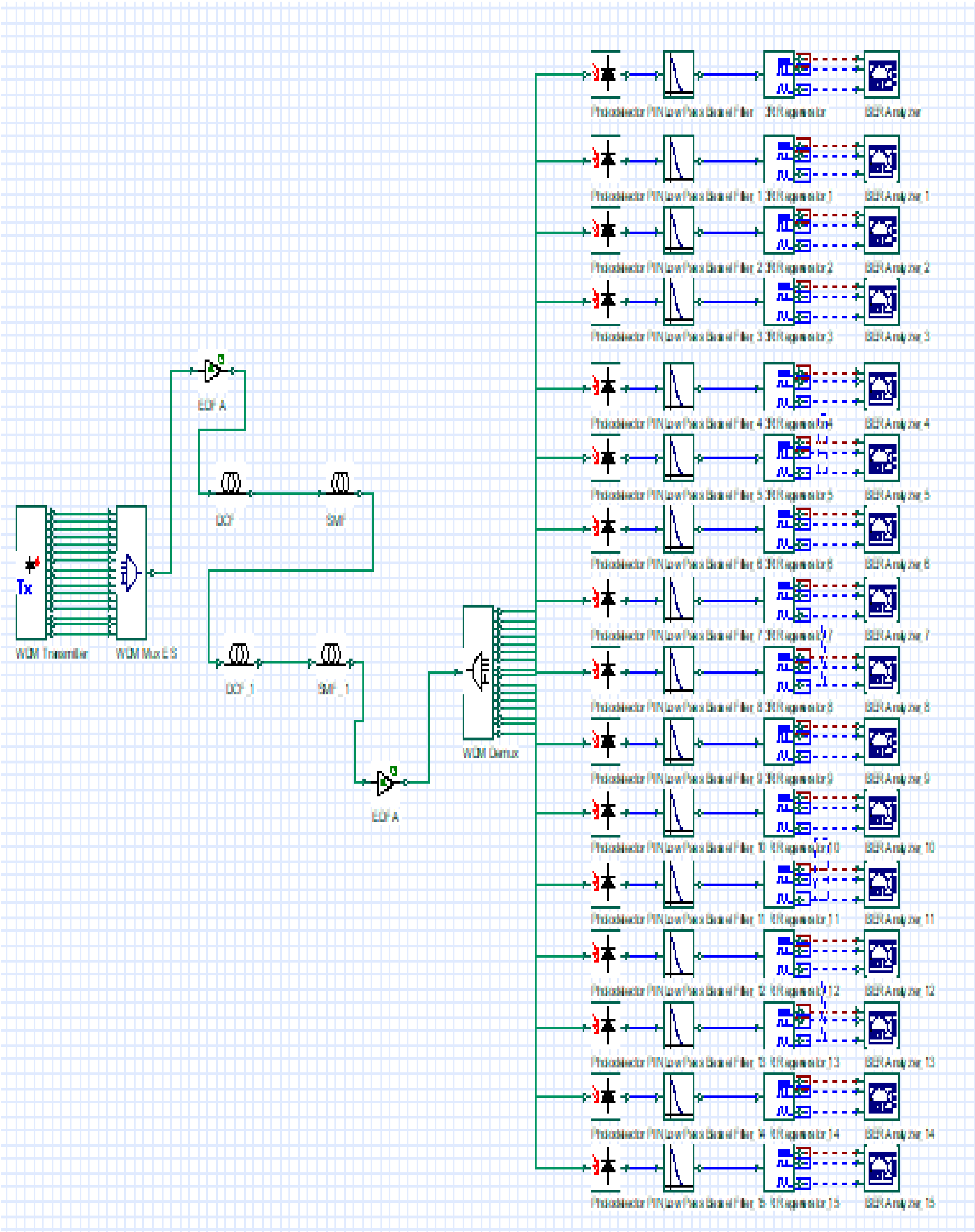


Figure 3.17: 16-channel WDM with 75-25 km SMF

Table 3.7: 16-channel WDM results 75-25 km SMF

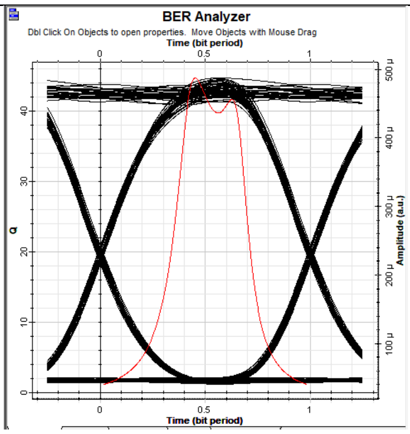
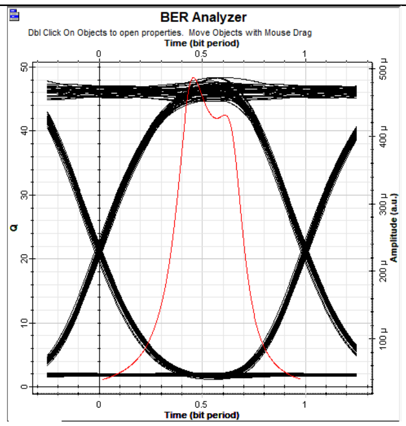
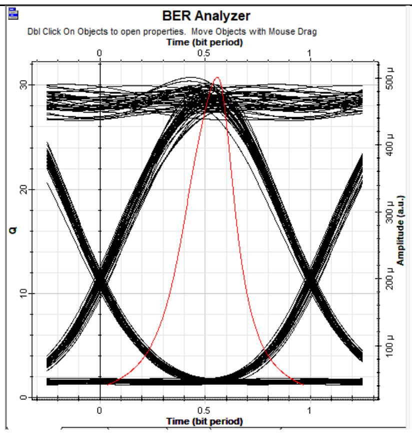
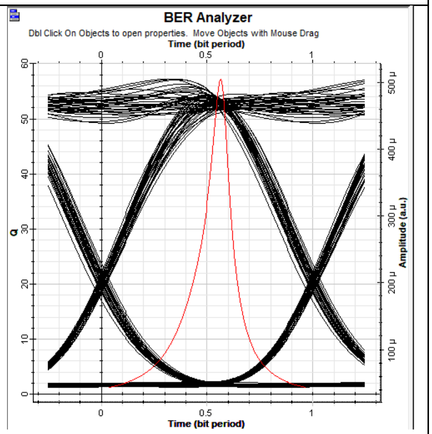
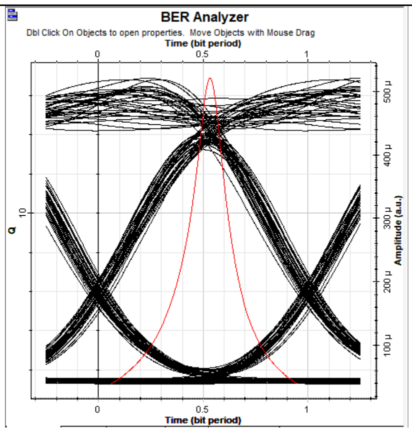
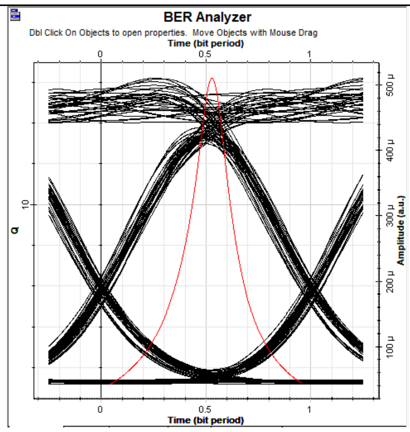
Bit rate (Gbps)	CH1		CH8		CH16	
	Q	BER	Q	BER	Q	BER
2.5	48.4784	0	48.981	0	36.3351	0
5	41.104	0	36.4297	0	44.432	0
7.5	16.1873	2.64e-59	12.9121	1.64e-38	15.5072	1.43e-54
10	6.2943	1.36e-10	6.1547	3.32e-10	6.3416	1.00e-10
12.5	3.9931	3.26e-5	3.2826	0.0004	4.0198	2.9e-5

Table 3.8: 16-channel WDM results 100 km SMF

Bit rate (Gbps)	CH1		CH8		CH16	
	Q	BER	Q	BER	Q	BER
2.5	44.6709	0	30.4606	0	44.1061	0
5	30.7441	0	25.8094	0	32.3481	0
7.5	16.8906	2.31e-64	16.294	4.73e-60	17.048	1.61e-65
10	6.0777	5.45e-10	5.8018	2.90e-9	5.8549	2.08e-9
12.5	4.0418	2.64e-5	3.6692	0.00012	3.8155	6.79e-5

The obtained eye diagrams are shown in table 3.9

Table 3.9: 16-channel WDM eye diagrams (ch1)

Bite rate (Gbps)	100km	75-25 km
2.5		
5		
7.5		

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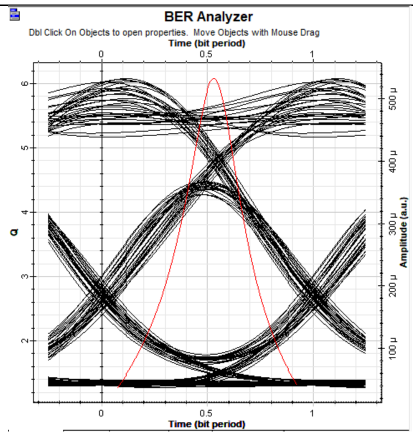
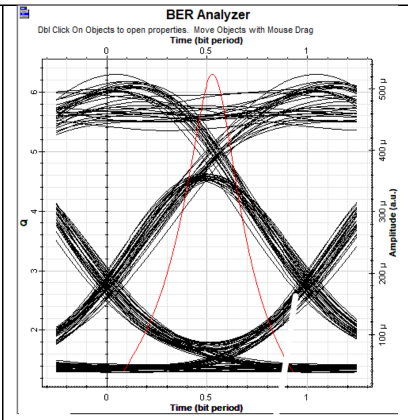
<tr><td>10</td><td>
</td><td>
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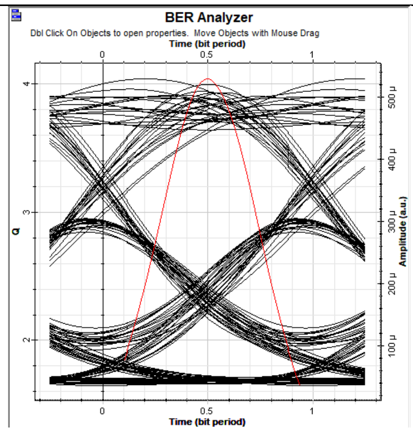
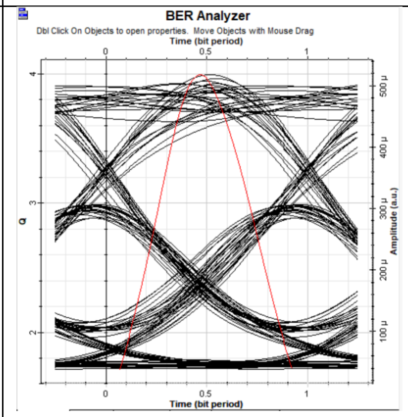
<tr><td>12.5</td><td>
</td><td>
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From tables 3.7, 3,8 and 3.9, the 75-25 km configuration gives higher Q factor and wider eye diagrams in all channels for the 5Gbps and 10Gbps bit rates, and in ch-1 and ch-8 for 2.5Gbps. Hence for the others bit rates the 100 km configuration results are better except in ch-16 for 12.5 Gbps.

CHAPTER 4:

GENERAL

CONCLUSION

Conclusion:

Dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along optical fibers. When considering the major implementation of optical fiber transmission, which involves some form of digital modulation, then dispersion mechanisms within the fiber cause broadening of the transmitted light pulses as they travel along the channel. This make each pulse broaden and overlaps with its neighbors, eventually becoming indistinguishable at the receiver input. This effect is known as intersymbol interference (ISI) which is the main cause of transmission error in modern optical fiber communication systems. Thus, an increasing number of errors may be encountered on the digital optical channel as the ISI becomes more pronounced. Signal dispersion hence, limits the maximum possible bandwidth attainable with a particular optical fiber to the point where individual symbols can no longer be distinguished.

Nowadays, employing the single-mode optical fibers eliminated entirely one type of dispersion (mode dispersion) and allowed to propagate the signal over large distances. However, with the higher transmission speeds gigabites per second another type of dispersion (the chromatic dispersion) became more and more essential on large distances. As the chromatic dispersion is the characteristic feature of the material (dependence of the refraction index on the wavelength for fused silica) it is impossible to avoid it, it can be only reduced.

Many techniques are used today to combat the negative effects of chromatic dispersion on optical fiber communication links, among them is the use of 'Dispersion Compensating Fibers' (DCF). This technique consists of adding to the main fiber link a special fiber having a negative dispersion parameter with a carefully calculated length in order to obtain a total dispersion of zero or to reduced significantly at least for a given transmission bit-rate.

In our work, we investigated this technique by simulation on a basic 4, 8 and 16-channel WDM optical fiber link.

The DCF technique can be used in three different configurations (pre-compensation, post-compensation and symmetric-compensation) depending on at which end of the fiber link the DCF fiber is connected to the main fiber.

The first step in our investigation is to determine the performance of each of these configurations on a fiber link of 100 km length at transmission bit-rates from 2.5GHz to 12.5GHz. The obtained simulation results based on BER/Q figures; show that the pre-compensation configuration gives the best performance under these operating conditions. Hence, the pre-compensation has been chosen as the most appropriate version of DCF compensation to go further in our investigation.

The next step was to determine whether the DCF (pre-compensation) technique gives better efficiency if the optical link is split into two or many shorter link parts. For this purpose, we have investigated six configurations; 100km full path, 50km-50km two parts, 25km-75km two parts, 30km-40km-30km three parts and 25km-25km-25km-25km four parts. The obtained simulation results taken from channel 1 of the 4-Channel WDM system presented in figure 3.13, show that as expected, the transmission performance decreases (Q factor decreases) as the transmission rate increases for all configurations. However, it is shown that unlike other configurations, some configurations (75km-25km and 50km-50km) exhibit an increase of the Q factor at lower transmission rates range, which passes through an optimal point around the 5Gbits per second rate. The 75km-25km configuration seems to be the most appropriate for this transmission rate. Furthermore, this configuration has relatively the best performance over the chosen transmission rate range.

The obtained simulation results on the 8 then 16-channel systems does not show a significant difference between the different channels.

As a future work we suggest to investigate the same configurations using other dispersion compensation technique such as FBG and digital filters

Appendix A: Eye Diagram

The eye diagram is an intuitive graphical representation of electrical and optical communication signals. The quality of these signals (the amount of inter-symbol interference [ISIJ, noise, and jitter) can be judged from the appearance of the eye. Eye diagrams frequently are used in the literature to document signals in optical receivers and transmitters. In the following, we explain how to produce eye diagrams from measurements and simulations. We also discuss how to determine the eye openings and eye margins of an eye diagram.

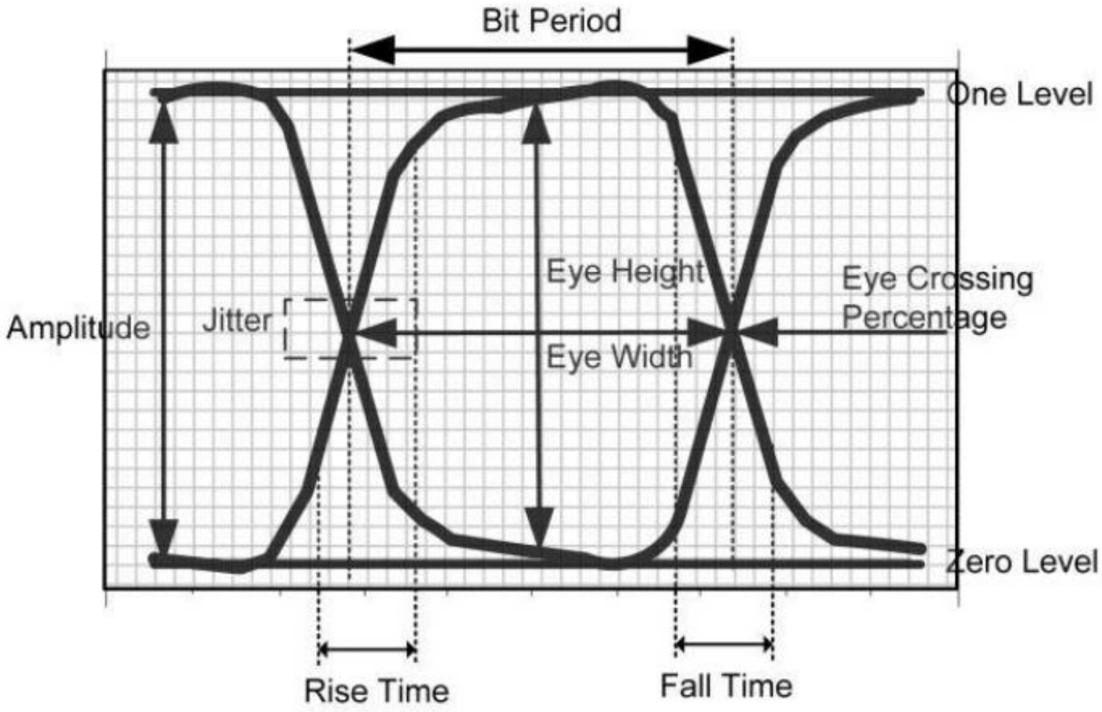

Figure 1 : Eye-Diagram Measurments .

- **One level:** the one level is an eye pattern is the mean value of a logic one. The actual computed value of the one level comes from the histogram mean value of all the data samples captured inside the middle 20 % (40 % to 60 % points) of the eye period.

- **Zero level:** The zero level in an eye pattern is the mean value of a logic zero. The zero level is computed from the same 40 to 60% region of the baseline area during the eye period as the one level.

- **Eye Amplitude:** Eye amplitude is the difference between the one and zero levels. The data receiver logic circuits will determine whether a received data bit is a “0” or “1,” based on the eye amplitude.

- **Eye Height**: Eye height is a measure of the vertical opening of an eye diagram. An ideal eye opening measurement would be equal to the eye amplitude measurement. For a real eye diagram measurement, noise on the eye will cause the eye to close. As a result, the eye height measurement determines the eye closure due to noise. The signal to noise ratio of the high speed data signal is also directly indicated by the amount of eye closure.

- **Eye Crossing Percentage:** The crossing level is the mean value of a thin vertical histogram window centred on the crossing point of the eye diagram. The eye crossing percentage is then calculated using the following equation:

$$Eye\ crossing\ (\%) = \frac{\text{crossing level} - \text{zero level}}{\text{one level} - \text{zero level}}.100$$

- **Bit Period:** The bit period is a measure of the horizontal opening of an eye diagram at the crossing points of the eye and is usually measured in picoseconds for a high speed digital signal. Bit period is the inverse of the data rate
- **Eye Width:** Eye width is a measure of the horizontal opening of an eye diagram. It is calculated by measuring the difference between the statistical mean of the crossing points of the eye.

- **Rise Time:** Rise time is a measure of the mean transition time of the data on the upward slope of an eye diagram. The measurement is typically made at the 20 and 80 percent or 10 and 90% levels of the slope.
- **Fall Time:** Fall time is a measure of the mean transition time of the data on the downward slope of an eye diagram. The measurement is typically made at the 20 and 80 percent or 10 and 90 percent levels of the slope.
- **Jitter:** Jitter is the time deviation from the ideal timing of a data-bit event and is perhaps one of the most important data signal. [24]

Appendix B: Transmission Band of WDM

Table 2: DWDM band wavelength range.

Band Name	Wavelengths (nm)	Description
O-band	1260 – 1360	Original band PON upstream
E-band	1360 – 1460	Water peak band
S-band	1460 – 1530	PON downstream
C-band	1530 – 1565	Lowest attenuation Original WDM band Compatible with fiber amplifiers CATV
L-band	1565 – 1625	Low attenuation Expanded WDM band
U-band	1625 – 1675	Ultra-long wavelength

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