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Performance Analysis of Dispersion Compensation using FBG and DCF in WDM Systems

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Dedication

Elhamdu li Allah , all praise and thanks to Allah for guiding me during this journey and giving me the strength to finish this work.

I'd like to dedicate this work to my beloved parents, that are always by my side supporting and loving me. To my mother MENADI Saliha, for her care and love and for my father BENAMROUCHE Mahmoud for his efforts in educating me and making me loving science and always curious about learning. I'd like to thank dad and mom for everything from the day they put a pen in my hand and taught me how to write the first letter until today.

To my sister Bouchra and to my brother Redouane for their endless love and support.

To everyone I met in my life and encouraged me in a direct or an indirect way. To all those who were supporting me in my hardest time, my friends: Sabrina, Youcef , Abderrahmane, Zahia, Mohammed Amine and AbdelKarim.

Lina

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A special thank goes to all my teachers during my studying process.

I owe special thanks to the honorable members of the jury who have agreed to evaluate my work.

Thanks to all the IGEE members.

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Abstract

This project is about studying several factors and dispersion compensators that affect the performance parameters in WDM optical fiber transmission systems. At frequency of 193.1THz with spacing frequency of 100Ghz. In the first part of the simulation, 4-Channel WDM system is designed and simulated. Only the results of channel 1 which got discussed as Q factors and eye diagrams dependent on change in distance, transmission rates and input power values, then on FBG and DCF added as dispersion compensators in different configurations. In the next part, 8-Channel WDM system is designed and simulated for 60Km transmission distance at 5GBit/s transmission rate and input power of 10dBm. The results of channels 1, 5 and 8 are discussed for different DCF and FBG techniques. Finally, 2-Channel WDM system is designed and simulated for 120Km, at 6GBit/s for input power of 10dBm. The results of channel 1 and 2 are discussed for multistage FBG and DCF techniques.

Keywords: WDM, Dispersion, FBG, DCF, Performance parameters.

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List of abbreviations

PRBS	Pseudo Random Binary Sequence
NRZ	Non-Return to Zero
LED	Light Emitting Diode
LASER	Light Amplification by Stimulated Emission of RadiationLight
EAM	Electro-Absorption-Modulator
MZM	Mach-Zehnder Modulator
TIR	Total Internal Reflection
SMF	Single Mode Fiber
MMF	Multi-Mode Fiber
SNR	Signal to Noise Ratio
BER	Bit Error Rate
PIN	Positive Intrinsic Negative
APD	Avalanche Photodiode
ISI	Inter Symbol Interference
WDM	Wave Division Multiplexing
DWDM	Dense Wave Division Multiplexing
SBS	Simulated Brillouin Scattering
SRS	Stimulated Raman Scattering
EDFA	Erbium-Doped Fiber Amplifier
RA	Raman Amplifier
SOA	Semiconductor Optical Amplifier
PSP	Principle State of Polarization
SOP	State of Polarization
OSNR	Optical Signal to Noise Ratio
Q factor	Quality factor
IR	Infra-Red
UV	Ultra-Violet
CW	Continuous Wave

DCF	Dispersion Compensating Fiber
FBG	Fiber Bragg Grating
EDC	Electronic Dispersion Compensation
LAN	Local Area Network
MAN	Metropolitan Area Network
TDM	Time Division Multiplexing
CATV	Cable Television
MUX	Multiplexer
DEMUX	De-Multiplexer
IDCFBG	Ideal Dispersion Compensation Fiber Bragg Grating

General Introduction

At present, in the domain of telecommunication, the optical fiber becomes the major telecommunication system used in many applications. Fiber optic system scheme contains three main components: a transmitter device that converts electrical signals into light signals; through the modulation process, an optical fiber cable that transmits light in its core; corresponding to the optical fiber transmission principle, and a receiver that detects light signals and converts them back to electrical ones.

The fiber transmission system has so many advantages. However, it is susceptible to attenuation, dispersion and other nonlinear impairments that limit its performance. Optical amplifiers are the technology used to solve the problem of optical power attenuation. While dispersion is the most complicated impairment that hampers the performance of optical fiber communication and limits the ultimate data rate supported by the fiber by increasing the inter chirp interference mainly at higher transmission speeds. To minimize dispersion so many technologies have been developed two of these technologies are Fiber Bragg Grating (FBG) and dispersion compensating fiber (DCF).

In this thesis, FBG and DCF techniques have been applied to different WDM systems at various data rates and input power. The systems have been simulated using OptiSystem software and studied. This work contains three main chapters that are organized as follows.

- **Chapter 1:** Introduces the optical communication system and its main components, the transmission principle, and WDM systems.
- **Chapter 2:** Introduces impairments in the optical fiber communication (attenuation and dispersion) and the technologies developed to compensate different types of impairments.
- **Chapter 3:** Simulation and study of WDM systems without dispersion compensation and with FBG and DCF compensation techniques at different transmission rates and for input power values.
- **Conclusion:** Summarizes the outcome of this work.

Chapter 01

Optical Fiber

Communication System

1.1 Introduction

The optical fiber system is a communication system similar to the other communication systems. However, the optical fiber system has an important role in the development of technology because of allowing high speed data transmission with a large frequency bandwidth. It provides transmission through transparent fiber optic cables made of glass or plastic while, the data has the form of light pulses that pass through it. This optical transmission makes the transmitter and the receiver stations unique such that a modulation system is needed in the transmitter and a detection one is needed in the receiver.

1.2 Fiber optic system main components

The fiber optic system consists of an optical transmitter, an optical channel, and an optical receiver. As shown is figure 1.1.

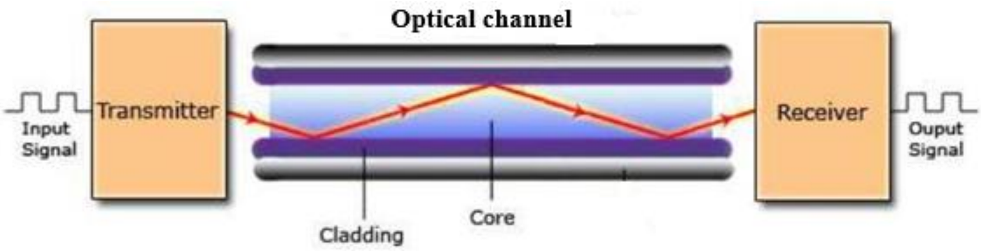


Figure 1.1 Basic optical fiber communication system

1.2.1 The optical transmitter

The optical transmitter receives electrical signals, then converts them into optical signals transmitted in an optical channel .It consists of an optical source, a device modulating optical radiation in accordance with input electrical pulses.

1.2.1.1 Pseudo random binary sequence (PRBS) generator

Pseudo random binary sequence generator is a digital device that generates the information to be transmitted represented in pseudo random bit sequence. Mainly used for simulation purpose as a source of information (audio, video, data….).

1.2.1.2 Non-return-to-zero (NRZ) pulse generator

Non-return-to-zero (NRZ) pulse generator receives the binary data generated by the PRBS generator in its input port and transforms it into electrical pulses without rest between any two bits. Unlike the return-to-zero coding technique. It is illustrated in the figure1.2.

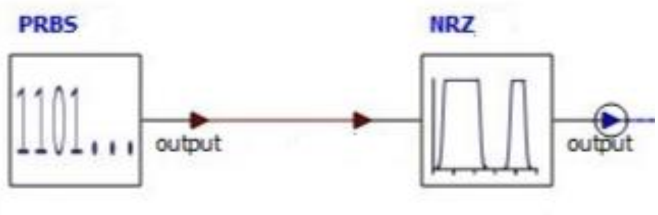


Figure 1.2 PRBS generator and NRZ pulse generator

1.2.1.3 Light source

In the optical telecommunication domain, two types of light sources can be used: light emitting diode (LED), or light amplification by stimulated emission of radiation (LASER).

a. Light emitting diode (LED)

is used in various applications. It is an active device, constructed by forward biased P-N junction of two semiconductors that emits light when electrons and holes recombine at the junction. The electrons in the conduction band are at a higher energy level and the holes are in valence band which is at the lower energy level. When high energy level electrons jump into valence band they release some amount of energy. For some semiconductors such as GaAsP (Gallium Arsenide Phosphide) and GaP (Gallium Phosphide) the released energy is in the form of light. [1]

b. Light amplification by stimulated emission of radiation (LASER)

It is also constructed as semiconductors' P-N junction where a photon is used to strike the electrons at higher energy state then as result of collision these electrons will become unstable due to high energy and energy imparted by the striking photon. Thus, this electron will move to lower energy state and release a photon in addition with the incident photon. This is called stimulated emission. A light beam is formed by emitted photons similar to the incident one. As result, the beam produced is coherent and monochromatic. [1]

1.2.1.4 Modulator

Modulation is an important step in the transmission process that can be performed without using an external modulator. This type of modulation is called direct modulation. In this type, the LASER changes the light intensity depending on the received electrical pulses. It is cheap and simple to implement but it has some disadvantages like chirp effect and very low speed of modulation. Because of these disadvantages, it is preferable to use an external modulator, as seen in figure1.3. There exists two common types of external modulators:

a. Electro-absorption modulator (EAM)

electro-absorption modulator is a semiconductor device for which the chosen material depends on the operating wavelength. By applying an external electric field, the bandgap energy is changed which means that the absorption spectrum is changed as well. This phenomenon is known as Franz-Keldysh Effect.

b. Electro-optic modulator (Mach-Zehnder-Modulator (MZM))

Mach- Zehnder Modulator is one of the most common external modulators. It works based on the change of the refractive index observed for some crystals under an external electric field. While the structure of Mach-Zehnder modulator and the interferometers inside of it, converts the induced phase modulation into intensity modulation. Figure 1.3 shows the role of an external modulator.

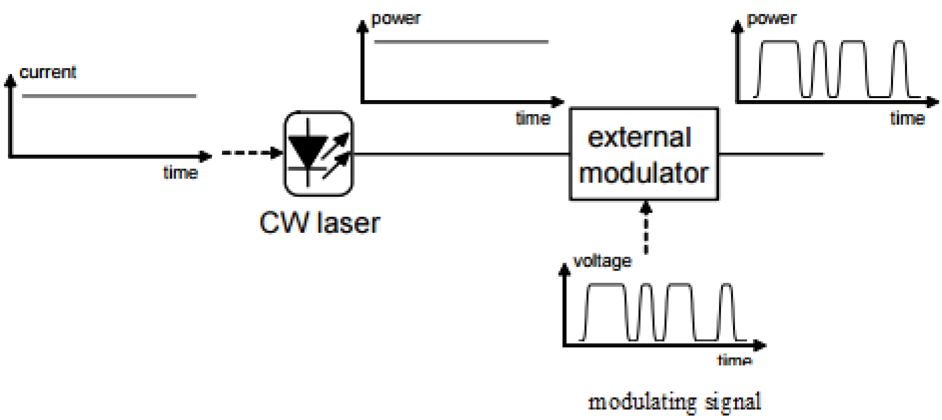


Figure1.3 External modulator added to the receiver system

1.2.2 The optical channel

The optical fiber is very thin cable. It is a waveguide made up of transparent dielectric materials; mainly glass or plastic; through which the light travels. It takes the place of copper cables in telecommunications because of its greater bandwidth, high speed and less losses and no heat is produced during transmission. It is composed of three main layers:

- **Core:** it is the central element through which the light travels. Its diameter varies depending on the amount of light travelling inside of it that depends on the used applications. The core is typically made of glass or plastic.

- **Cladding:** is the element that surrounds the core. It reduces light scattering and it is an essential element that makes the total internal reflection principle verified. It protects the core from outside contaminants.

- **Coating:** is the element that protects both the core and the cladding from any physical damage. It is thicker than the cladding. It comprises layers of plastic material.

The optical cable contains others layers that surround the coating for more protection and less losses. Figure 1.4 represents the main layers of the optical cable.

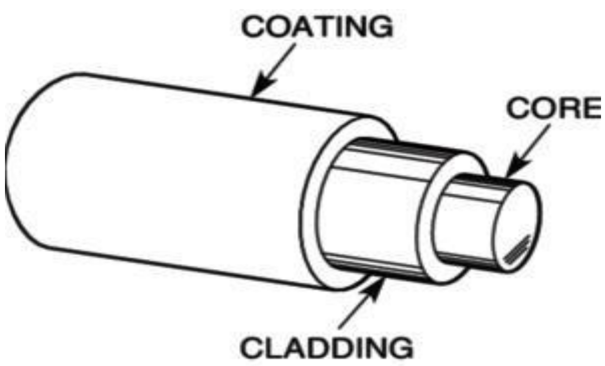


Figure1.4 the optical cable structure

1.2.2.1 Transmission principle

The transmission principle is the mechanism by which light propagates (theoretically with no attenuation) inside an optical fiber. It is based on the total internal reflection (TIR) principle.

a. Denser and rarer media

In the optical domain, media can be classified into two types: a denser medium where the speed of light is less and the refractive index is greater, and a rarer medium where the speed of light is higher and the refractive index is less.

When light travels from a rarer medium to a denser one the refracted ray bends toward the normal (the line that is perpendicular to the boundary between the two media) and the angle of refraction (the angle between the refracted ray and the normal) is less than the angle of incidence (the angle between the incident ray and the normal). However, when light travels from a denser medium to a rarer one, the refracted ray bends away from the normal and the angle of refraction is greater than the angle of incidence. Figure 1.5 clarifies these refractions.

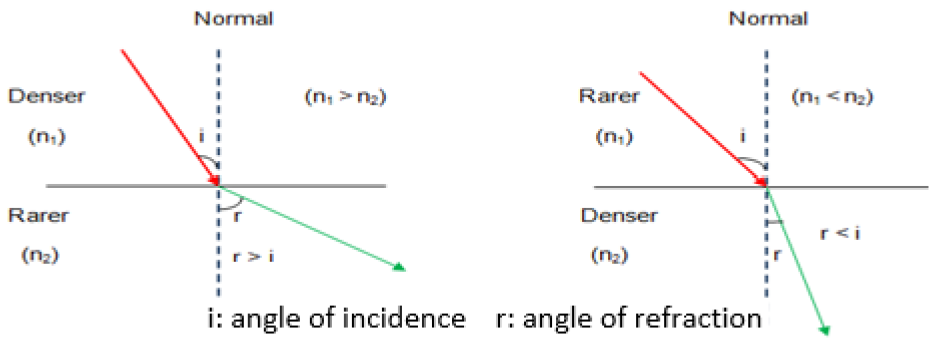


Figure1.5 Refractions in denser and rarer media [2]

b. Total internal reflection (TIR)

The total internal reflection is the exact principle that makes the light travels inside the core of the fiber. It is based on two conditions:

- The light must travel from the denser medium (the core) to the rarer one (the cladding); while the refractive index of the core is slightly greater than the refractive index of the cladding; such that it goes away from the normal and can reflect in a smooth way.
- The angle of incidence must be greater than the critical angle: which makes the light return back to the denser medium.

The critical angle is the angle of incidence that makes the ray refract perpendicularly to the normal. Any incident angle greater than the critical one makes the light reflect. Figure 1.6 clarifies the meaning of critical angle.

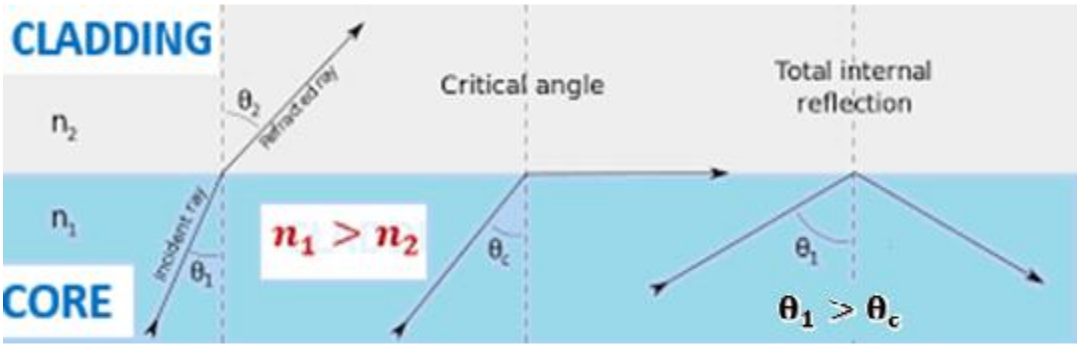


Figure1.6 The critical angle

To determine the critical angle, Snell's law must be introduced.

- **Snell's law :** is the law which makes us determine the critical angle and respect the second condition of the TIR principle.

$$\mathbf{n_1 \sin\theta_1 = n_2 \sin\theta_2} \qquad (1.1)$$

$\mathbf{n_1}$: The refractive index of the core

$\mathbf{n_2}$ **:** The refractive index of the cladding

$\boldsymbol{\theta_1}$ **:** The incidence angle

$\boldsymbol{\theta_2}$ **:** The refractive angle

If $\boldsymbol{\theta_1 = \theta_c}$ then $\boldsymbol{\theta_2 = 90°}$

By replacing the values of the precedent angles in $(\mathbf{1.1})$ we get:

$$\boldsymbol{\theta_c = \sin^{-1}\frac{n_2}{n_1}} \qquad (1.2)$$

c. The acceptance cone

It is explained in the total internal reflection principle that the incident angle must be greater than the critical one. But in fact, the incident angle from the core to the boundary between the core and cladding depends on the launching ray from the air to the core. The launching angle between the launching ray and the core axis (the core axis is the normal to the boundary between air and the core) must be fixed such that the refracted ray release the TIR principle.

We know that air has the smallest refractive index so it is considered as a rarer medium, and the core as a denser one, which means that the refracted ray bends toward the axis of the core and never reflects. However, it must create an incident angle (between the core and the cladding) greater than the critical one.

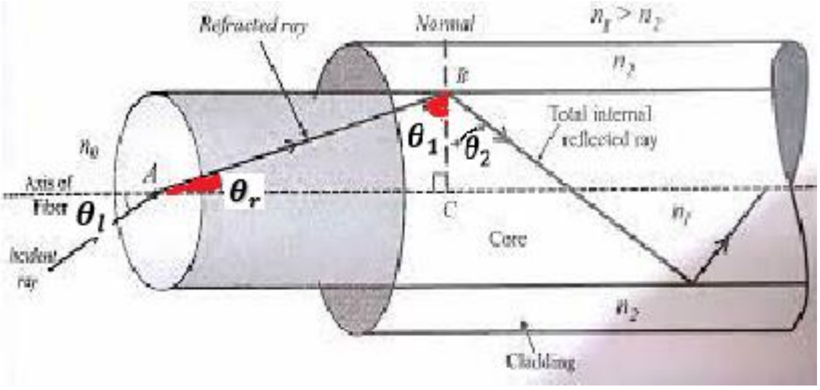


Figure1.7 The launching angle

From figure 1.7, we can notice that: $\boldsymbol{\theta_r + \theta_1 = 90°}$ $\quad (\mathbf{1.3})$

By applying Snell's law to air-core interface: $\mathbf{n_0 \sin\theta_l = n_1 \sin\theta_r}$ $\quad (\mathbf{1.4})$

$\boldsymbol{\theta_1}$ **:** The incidence angle (core-cladding interface)

$\boldsymbol{\theta_2}$ **:** The reflected angle (core-cladding interface)

$\boldsymbol{\theta_r}$**:** The refracted angle (air-core interface)

θ_l: The launching angle (air-core interface)

n_0 : The refractive index of air

From $(\mathbf{1.3})$ **:** $\boldsymbol{\theta_r = 90° - \theta_1}$ $\quad (\mathbf{1.5})$

By replacing $(\mathbf{1.5})$ in (1.4) : $n_0 \sin\theta_l = n_1 \sin(90° - \theta_1)$

So: $n_0 \sin\theta_l = n_1 \sin(90° - \theta_1)$

Then: $\mathbf{n_0 \sin\theta_l = n_1 \cos\theta_1}$ $\quad (\mathbf{1.6})$

We can notice that when θ_l increases $\sin\theta_l$ increases which means that $\cos\theta_1$ increases. If $\cos\theta_1$ increases then θ_1 decreases. It can be deduced that θ_l must be less than a maximum value which makes θ_1 always greater than the critical angle. The maximum value of the launching angle is called the acceptance angle: θ_a .and it can be determined by replacing in **(1.6),** $\boldsymbol{\theta_1}$ *by* $\boldsymbol{\theta_c}$ *and* $\boldsymbol{\theta_l}$ by$\boldsymbol{\theta_a}$: $\mathbf{n_0 \sin\theta_a = n_1 \cos\theta_c}$

with $\mathbf{n_0} = 1$ (air) and $\boldsymbol{\cos\theta_c = \sqrt{1 - \frac{n_2^2}{n_1^2}}}$ (from **(1.2)**)

Then: $\boldsymbol{\theta_a = \sin^{-1}\sqrt{n_1^2 - n_2^2}}$ $\quad (\mathbf{1.7})$

(1.7) represents the acceptance angle. However, the optical cable has three dimensions, which determines the acceptance cone that surround the fiber, and the acceptance cone is twice the acceptance angle, as shown in figure 1.8.

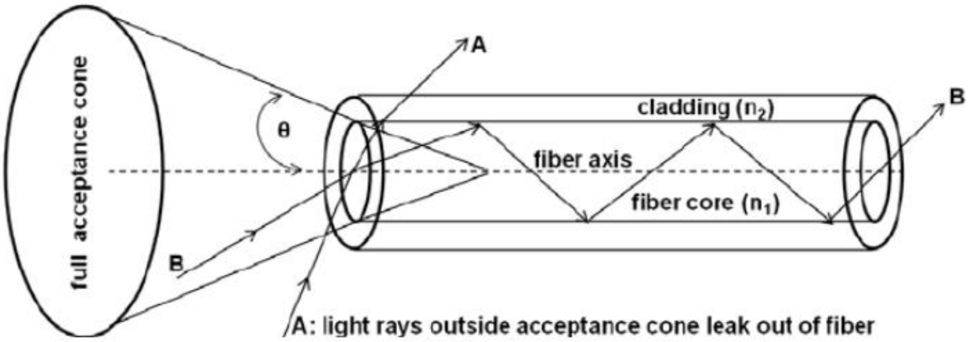


Figure1.8 The acceptance cone [3]

1.2.2.2 Modes of propagation in the optical fiber

The directions along which the incident ray can propagate through the fiber are called modes of propagation. The optical fiber supports a set of discrete modes based on the propagation angle. When the fiber supports only one allowed direction, it is called a single mode fiber (SMF) otherwise it is a multimode fiber (MMF). Figure 1.9 represents these different modes.

a. Single mode fiber

Single mode fibers have a small core radius, which does not allow the wave to propagate in more than one direction. Therefore, the single mode fiber travels without reflections and through a straight line. Hence, the losses are reduced allowing the signal to travel for long distances.

- **Step index single mode fiber:** refers to the refractive index profile of the core and the fiber. In step index profile, the core has a constant value for the refractive index, which falls suddenly at the cladding interface and gets its refractive index value.

b. Multimode fiber

The core of the multimode fiber is larger which allows the wave to travel inside of it, in different directions. However, the number of allowed modes does not depend only on the diameter of the core, but also on the constructive interference, which means that only the zigzag paths that are in phase, that can propagate through it.

Losses increases in the multimode fiber because of reflections, therefore, it is better to avoid it in long distance communications.

- **Step index multimode fiber:** it has the same shape of the refractive index profile, as explained in the step index single mode fiber. The sudden change in the refractive index value creates zigzag paths through which the light propagates and the waves arrive at different times causing dispersion.
- **Graded index multimode fiber:** the refractive index of the core varies along its radius. It has a maximum value at the center and decreases gradually towards the core cladding interface, where it matches with the refractive index of the cladding. Which makes the waves refract at each different value of the refractive index along the core towards the cladding, which creates a process that leads to similar results as the TIR principle. However, the paths are smooth, parabolic and simultaneous.

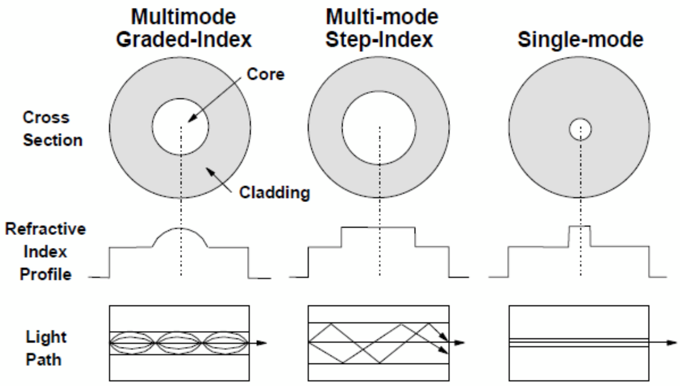


Figure1.9 Modes of propagation [4]

1.2.3 The optical receiver

The optical receiver consists of three main stages to decode the received optical pulses and generates an electrical data stream proportional to it, such that some requirements must be satisfied, for example: signal to noise ratio (SNR) and bit error rate (BER).

The design of an optical receiver is more complicated than the one of the optical transmitter, because it must be able to detect weak, distorted signals.

1.2.3.1 Optical detector

Optical detectors are photodiodes that convert light pulses into electrical signals. The most common photodiodes are: positive intrinsic negative (PIN) photodiodes and avalanche photodiodes (APD)

a. Positive intrinsic negative (PIN) photodiode

PIN photodiode consists of a very thick intrinsic depletion region between positive and negative extrinsic doped regions, because it works in the reverse bias. The depletion layer is free of any carriers so that, no current flows. However, when a photon strikes the intrinsic region an energy in supplied to it, causing motion of an electron-photon pair in opposite directions. This phenomenon creates a flow of a small current proportional to the penetrated amount of light.

PINs are the most commonly employed detectors in fiber optic communication systems due to their ease in fabrication, high reliability, low noise, low voltage and relatively high bandwidth. [3]

b. Avalanche photodiode (APD)

The avalanche photodiode consists of a similar structure and principle to that of the PIN photodiode. However, it operates under a high reverse bias condition. As a photon enters the depletion region and creates a hole-electron pair, these charge carriers will be pulled by the very high electric field away from one another with a high speed, which makes them strike the other electrons and causing other electron-hole pairs motion repeatedly, and creating a bigger electric current. This phenomenon is known as: avalanche multiplication that provides a high gain of the diode and a very high sensitivity. [4]

1.2.3.2 Linear channel

The output current of the detector is very small; a front-end high gain amplifier boosts it to a level that enable it to be processed in the next devices. After the amplification, the signal passes through a law pass filter to reduce the noise, minimize inter symbol interference (ISI) and reshape the pulses that become distorted as they travel through the fiber [5]

1.2.3.3 Decision circuit

The decision circuit decides whether a one or a zero pulse is received, by comparing the output of the linear channel to a threshold level. The clock-recovery circuit is used (in chase of non return to zero format) to determine the bit period, such that the best sampling time corresponds to the situation in which the signal level difference between one and zero bits is maximum .the binary data is represented in time slot of duration T referred to as bit period. Figure 1.10 shows the bloc diagram of the receiver system. [5]

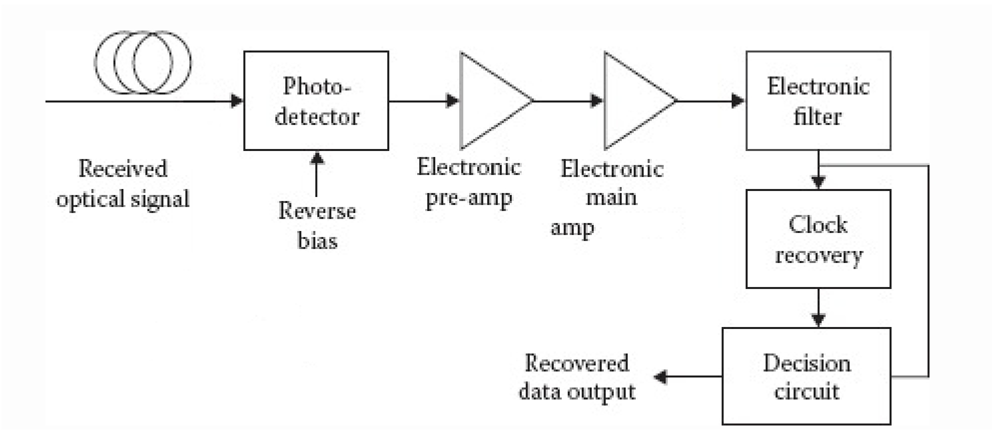


Figure1.10 Bloc diagram of the receiver system [8]

1.3 Wavelength division multiplexing (WDM) systems

Wavelength division multiplexing is a technology where multiple wavelength signals can be transmitted through the same single mode optical fiber as lightwaves of different lengths do not interfere with each other, Each one representing information stream. The transmission bigger capacity of the fiber makes the cost of installing a new fiber avoided. [6]

Optical signals from fiber optic terminals are converted into controlled wavelengths and multiplexed, then transmitted into a single fiber. The received signals are demultiplexed and delivered as individual signals to the receiver. [6]

The development of dense wavelength division multiplexing (DWDM) allows hundreds of channels to get multiplexed, and transmitted into the same optical cable which increases the capacity of data transmission bandwidth. However, the losses are more significant and have to be compensated. Figure 1.11 represents a WDM system.

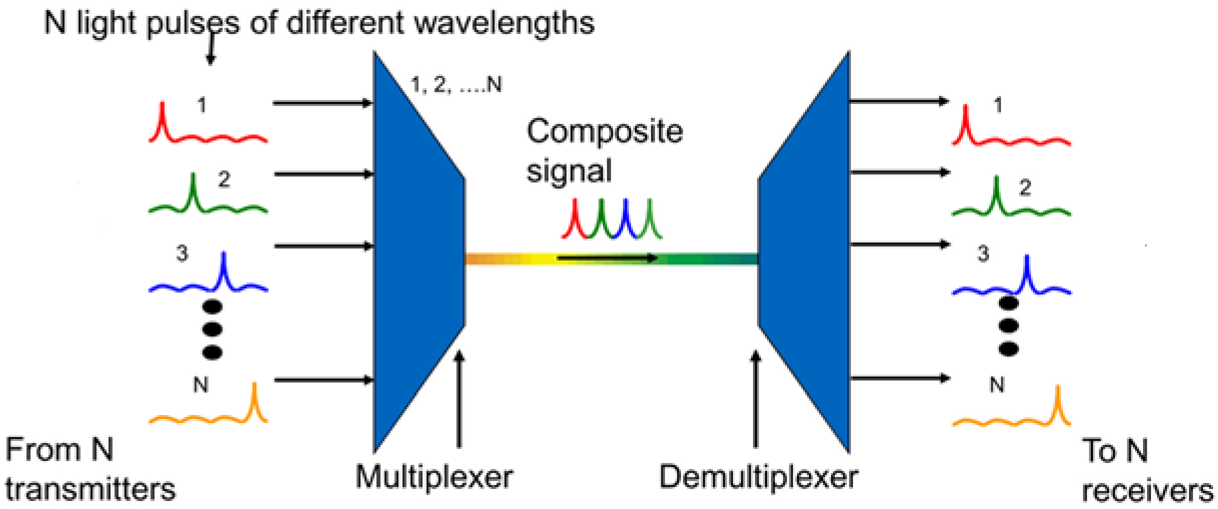


Figure1.11 Wavelength division multiplexing (WDM) [10]

1.4 Parameters affecting the optical system

In fiber optic systems, to ensure that the data is received in a good quality and the losses do not affect the content of the information, some parameters must be considered as optical signal to noise ratio (OSNR), Q factor and bit error rate (BER).

- **Optical signal to noise ratio (OSNR):** is the most important performance parameter. It is the ratio of the optical signal power (S) to the system noise power (N) in decibels expressed in dB, by: $OSNR = 10Log\left(\frac{S}{N}\right)$. OSNR affects other parameters in the system as BER so that it must be greater than a threshold value of about 15dB to 18 dB at the receiver to make it able to distinguish the signal that holds the information from the noise signal. [7]
- **Q factor:** is a measure of the quality of the received signal in terms of optical signal to noise ratio (OSNR) which takes into consideration all the disturbances that degrade the signal and cause bit errors. The Q factor is expressed in decibels, by the expression: $Q_{dB} = 20\sqrt{OSNR}\sqrt{\frac{B_o}{B_c}}$ such that: OSNR: Optical signal to noise ratio.

  B_o: is the optical bandwidth of the photodetector (receiver device).

  B_c: is the electrical bandwidth of the receiver filter.

- **Bit error rate (BER):** describes the probability of having an erroneous bit from the received bits. Given by the expression: $\mathrm{BER} = \frac{\mathrm{n}}{\mathrm{N}}$, while N is the total numbers of received bits and n is the number of erroneous received bits. BER can be determined in terms of the Q factor by: $BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right)$

  Where *erfc* function is the complementary error function defined as:

  $erfc(x) = 1 - erf(x)$, while *erf* function is the error function, defined as:

  $\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\, dt.$

  When the system has a good quality factor, the BER should be as small as possible, as seen in figure1.12. In WDM systems, BER is between 10^{-9} and 10^{-12} for an acceptable quality factor. [8]

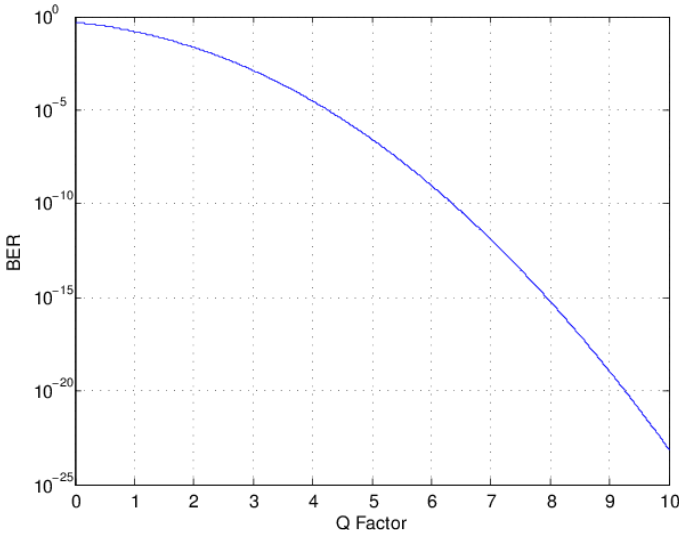


Figure 1.12 BER versus Q factor [13]

1.5 Conclusion

In this chapter, the optical fiber system and its components are described at different stages. It has been concluded that the optical fiber is the preferred medium for the data transmission but it is not perfect and the transmission process got affected by several types of losses that will be treated in the next chapter.

Chapter 02

Impairments in optical fiber transmission

2.1 Introduction

In telecommunication, the transmission of information is not perfect. The use of optical fibers and the new technologies around it facilitate the transmission process and increase the data rate. In the optical channel the information is transmitted as light pulses that are exposed to different external and internal interactions with the space around it, causing several types of impairments as attenuation and dispersion. These impairments have to be minimized and compensated for that, compensation techniques have been developed. In this chapter, optical transmission impairments and compensation techniques are discussed.

2.2 Attenuation in optical fiber

Attenuation is the loss of an optical power while the light travels along the optical cable. It is represented by a decrease in the amplitude of light intensity.

Mathematically, attenuation per distance unit is expressed in dB/Km, by the following expression: $\propto = \frac{10}{L}\log\left(\frac{P_i}{P_o}\right) {}^{dB}/_{Km}$. Such that: P_i: is the optical input power.

P_o: is the optical output power.

L: is the transmitted fiber length.

Attenuation is caused due to different types of imperfection in transmitting the optical power through the optical cable. The figure 2.1 shows the attenuation in power versus transmission length.

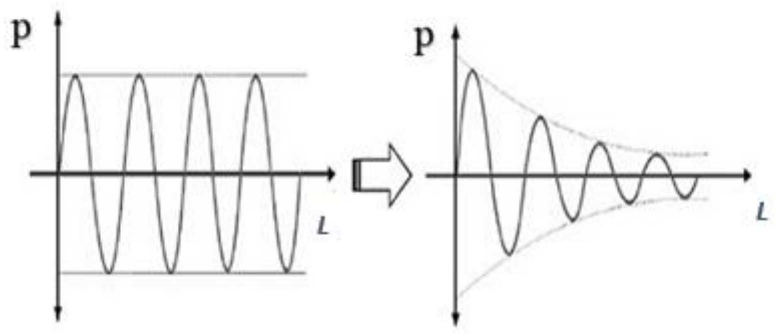


Figure 2.1 Optical power attenuation

2.2.1 Intrinsic attenuation

In the fabrication of the optical cables, some impurities must be added to the main substance basically to create the refractive index variations. These impurities lead to two different types of intrinsic attenuation: material absorption and scattering.

2.2.1.1 Material absorption

Material absorption is absorption due to the materials constructing the fiber cable. It can be due to the main material or due to the impurities. Absorption is uniform which means that the same amount of the same material absorbs the same fraction of light at the same wavelength accumulatively.

a. Intrinsic material absorption:

Intrinsic absorption occurs in the major pure material because of its basic structure. It is due to two mechanisms, which are:

- **Electronic absorption**: bands in UV region due to electronic absorption when a light particle (photon) interacts with an electron in the valence band and excites it to a higher energy level.
- **Atomic vibration bonds**: near IR region is caused by the interaction between the vibration bonds and the electromagnetic field of the light wave which is transferred to the bond (bond such as Si-O of the glass silica).

The intrinsic absorption can be controlled by choosing the best major materials for the core and cladding.

The intrinsic absorption loss is minimized near the IR region, around the operating wavelength range from 800 nm to 1700 nm.

b. Extrinsic material absorption:

Extrinsic absorption is caused by the impurities added to the major material in the fabrication of the optical cable as: $Cu^{2+}, Fe^{2+}, Ni^{2+}$. It results from transition of electrons from a level to an other inside the atom of any extrinsic atom, between the different atoms or when hydroxyl ions (OH^-) dissolved in glass. The presence of OH^- and hydrogen is caused by the presence of the water that inters the cable material from humidity, manufacturing process or chemical reaction. It appears as overtones at specific wavelengths.

A minimum amount of the metallic impurities and hydroxyl ions must be used to reduce this kind of absorption.

2.2.1.2 Scattering loss

The density fluctuations and changes within fibers are produced when the fibers are manufactured. Regions of higher and lower molecular density areas relative to the average density are created. When the light travels through the fiber, it interacts with the density areas and get scattered in different directions.

a. Linear scattering

Linear scattering mechanism causes the transfer of some or all of the optical power from one mode to another linearly. This process results attenuation of the transmitted light as the transfer can be to a leaky mode and does not continue to propagate within the fiber core. In linear scattering there is no change in the frequency. It can be categorized as:

- **Rayleigh scattering:** It is the dominant intrinsic attenuation loss mechanism between the ultraviolet and the infrared regions. It occurs in very small inhomogeneities comparing to the wavelength as refractive index fluctuations and increases at the density of compositional variations that can be avoided during the manufacturing process. However, the index fluctuations caused by only the freezing-in of density inhomogeneity are fundamental and exist in all directions producing an attenuation proportional to $\frac{1}{\lambda^4}$
- **Mie scattering:** unlike Rayleigh scattering, Mie scattering occurs at inhomogeneities which are comparable in size with the guided wavelength and created mainly in the forward direction. It results from imperfections of the fiber structure such as diameter fluctuations, strains and bubbles, core-cladding interface irregularities. Mie scattering can be reduced by: removing imperfections due to the manufacturing process, carefully controlled coating of the fiber and increasing the fiber guidance by increasing the relative refractive index difference.

b. Non-linear scattering

Non-linear scattering occurs at high optical power levels obeying nonlinear principle of propagation. It causes the optical power from one mode to transfer in either the forward or the backward direction within the same mode or other modes, at a different frequency. It occurs only above a threshold power level, which makes it easy to be avoided by choosing power levels less than the threshold one. This scattering mechanism appears more in the single mode fibers because for multimode fibers the diameter is large enough so that the threshold power is high. In fact, this mechanism give optical gain but it is considered as attenuation because of the frequency shift. There exist two types of non-linear scattering loss : stimulated Brillouin scattering and stimulated Raman scattering.

- **Stimulated Brillouin scattering (SBS):** It may be regarded as the modulation of light through thermal molecular vibrations within the fiber. It is based on frequency shift such as the scattered light appears as upper and lower sidebands which are separated from the incident light by the modulation frequency. The incident photon in the scattering process produces an acoustic phonon (mode of vibrational energy) of low frequency (sound frequency) as well as a scattered photon producing an optical frequency shift which varies with the scattering angle. The frequency shift is maximum in the backward direction and reduced to zero in the forward one. Brillouin threshold power is given by:

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \upsilon \ (watt)$$

Such that: d: is the fiber core diameter

λ: is the operating wavelength

α_{dB}: is the fiber attenuation in decibels per kilometer

υ: is the source bandwidth in gigahertz [9]

- **Stimulated Raman scattering (SRS):** is similar to SBS except that in the scattering process instead of generating an acoustic phonon, a high frequency optical phonon is generated. In a particular fiber, it has an optical power threshold three times higher in amplitude than the Brillouin threshold.

Intrinsic attenuation losses depending on wavelengths are shown in figure 2.2.

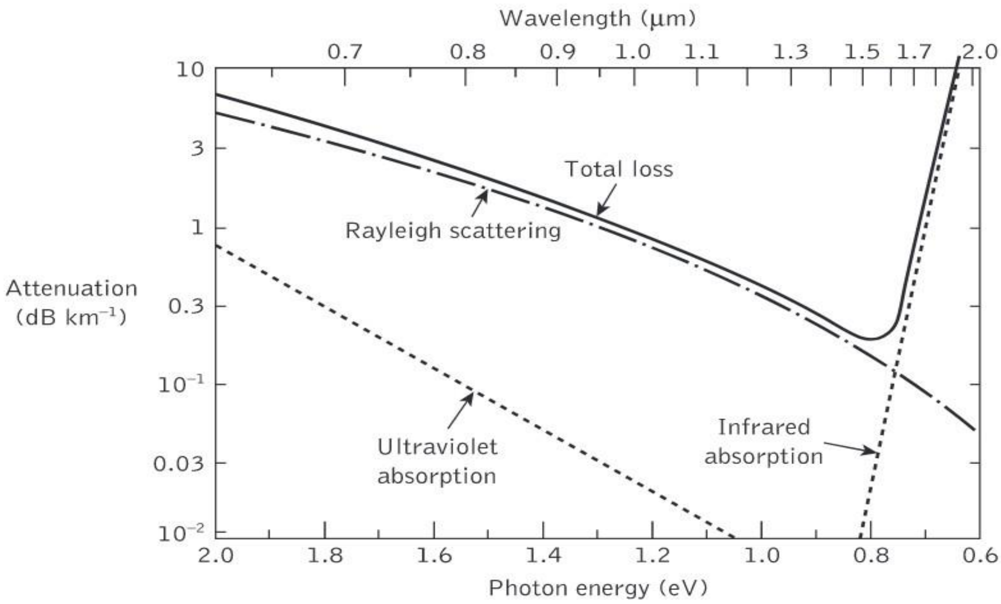


Figure 2.2 Intrinsic attenuation losses depending on wavelengths

2.2.2 Extrinsic attenuation

Extrinsic attenuation is an external attenuation happens generally when the optical fiber is bent as in figure2.3, or connected to another fiber.

The optical fiber can get bent in different physical manners in the manufacturing process or in the transmission roads; two types of bending are present: micro banding and macro bending.

- Micro bending: is a loss due to a small bending and micro scale fluctuations. Either at the core or the cladding undergoes slight bends at its surface. It occurs during the manufacturing process or it is caused by the environment temperature and pressure. This phenomenon affect the TIR principle by changing the angle of incidence at the bending point so that the ray does not reflect and it escapes outside the cable.

- Macro bending: When a fiber is bent through a large angle and strain is placed at the region of bending during the installation of the fiber cables. It can be eliminated just by straitening the cables. This is a large scale bending where the fiber bend exceeds an allowed radius that is called fiber bend radius. Whenever the bending is larger than the fiber bend radius the TIR principle is not respected and the rays refract.

The splicing losses are the losses resulting from the junction of two connected cables which refers to the part of power radiated through the junction regions. A special care is needed to minimize this type of losses.

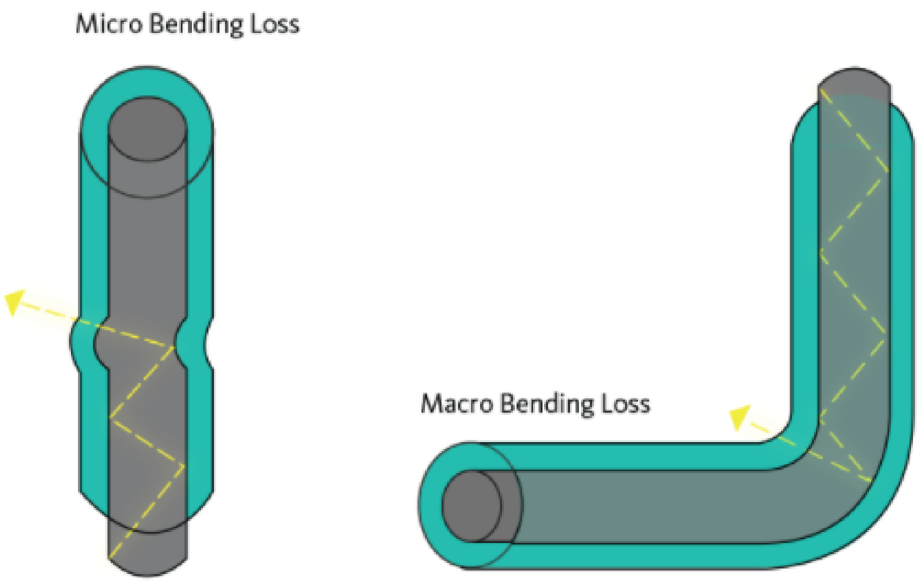


Figure 2.3 Bending losses [15]

2.3 Dispersion in optical fiber

Dispersion is the biggest problem is optical fiber communication. It is a loss of information due to the broadening of the pulses in the signal as they travel along the channel , which can cause inter symbol interference (ISI). This limits the maximum possible bandwidth and so the information carrying capacity of the optical cable such that the digital bit rate is related to the broadened pulse duration by: $B_R \leq \frac{1}{2\tau}$. B_R and τ , are the bit rate and the pulse duration respectively.

Dispersion has different sources that will be explained in the following parts.

2.3.1 Intramodal (chromatic) dispersion

The chromatic dispersion is the distortion of the signal caused by the variation in the phase velocity of light according to the wavelength. Each pulse is going to broaden according to the different wavelengths with different speeds through the cable. As it travels for long distance the difference between the wavelengths' distances increases, which broaden the pulse more and more, resulting pulse overlapping and ultimately bit errors. Chromatic dispersion has two types: material dispersion and waveguide dispersion.

2.3.1.1 Material dispersion

Material dispersion is due to the material that is used to manufacture the fiber and it depends on its refractive index as a function of the optical frequency. Each spectral component travels with different velocity (phase velocity) but we consider the group velocity. The spectral width can be limited at the source but it can be created due to the modulation. [10]

2.3.1.2 Waveguide dispersion

The waveguide dispersion is due to the energy distribution decided by the wavelength, according to this distribution only about 80% of the energy is confined into the core and the remaining 20% travels in the cladding with a higher speed (because of its lower refractive index). It is illustrated in figure 2.4.

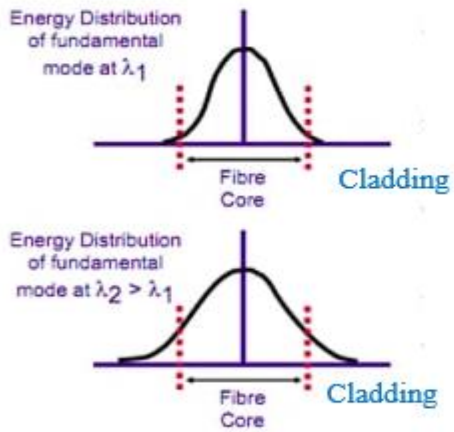


Figure 2.4 Energy distribution causing waveguide dispersion

The waveguide dispersion can be manipulated in such a way at a specific wavelength it cancels the chromatic dispersion when it is added to the material one. This is known as zero dispersion-shifted fiber. An example of zero dispersion-shifted fiber is shown in figure 2.5.

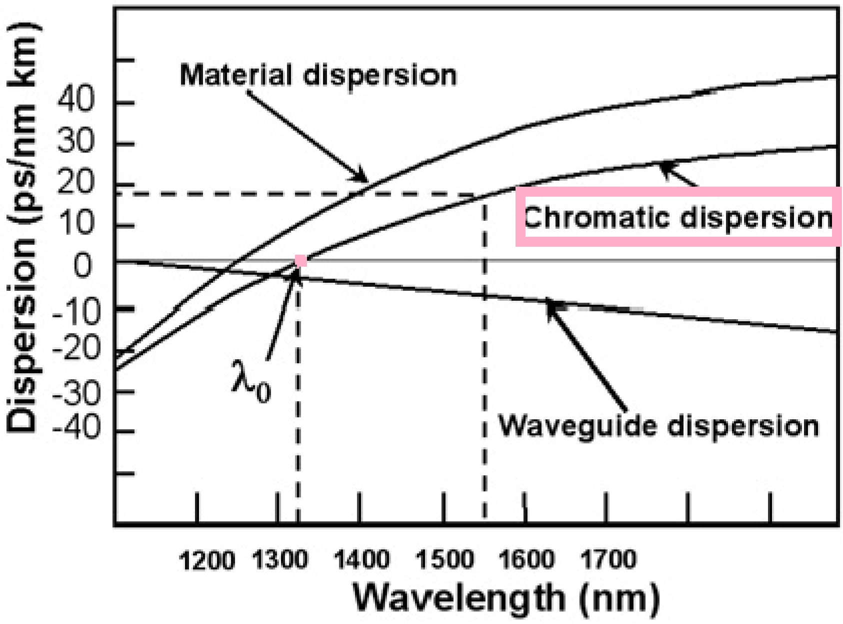


Figure 2.5 Example of zero-dispersion shifted fiber [17]

2.3.2 Intermodal (modal) dispersion

Intermodal dispersion (modal dispersion) mainly exists in multimode fiber where the dispersion does not only depend on the optical frequency as in chromatic dispersion, but it depends on the number of modes involved. The higher order the modes, the slower the group velocity obtained. To avoid strong signal distortion, it is usually necessary to keep the pulses long enough to maintain a reasonable temporal overlap of components from different modes, and this unavoidably sets a limit on the data rate. In order to avoid this kind of dispersion, the parabolic refractive index (graded index) fiber is used instead of step index fibers.

2.3.3 Polarization mode dispersion

The physical shape of the optical cable is not perfect because of the manufacturing process that cannot respect the mathematical dimensions perfectly and because of the mechanical stress exerted upon the fiber due to the weather, which results geometrical fluctuations in the fiber cable that is the main reason for a phenomenon called birefringence.

Core stress, cladding eccentricity and elliptical fiber design are some imperfect fiber design causing birefringence. While, fiber twist, fiber stress and fiber bend are examples of external stress causing birefringence.

As light is an electromagnetic wave that is combination of an electric field (E) and a magnetic field (H) that are perpendicular to each other and to the direction of propagation. They propagate simultaneously creating a light pulse. However, due to the birefringence, the electric and the magnetic field loose the balance and get separated from each other during the process of transmission creating a broaden pulse. This is known as polarization mode dispersion, as illustrated in figure 2.6. [11]

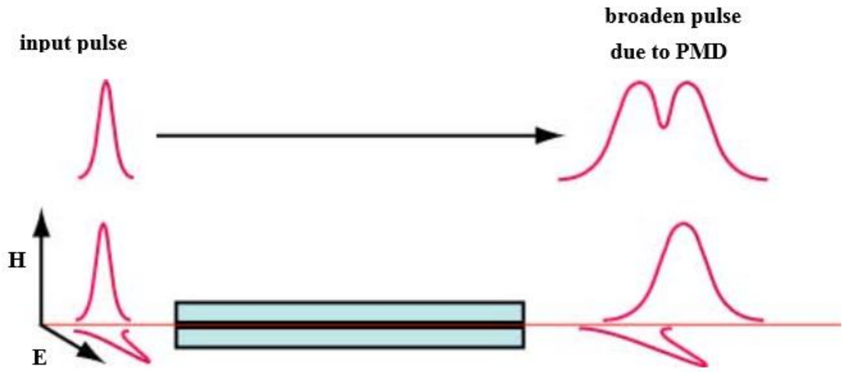


Figure 2.6 Polarization mode dispersion [19]

Note: attenuation and dispersion losses are due to both linear and nonlinear types of losses. While other nonlinear losses are clearly present in the fiber optic communication in different stages such as self-phase modulation, cross-phase modulation and four wave mixing.

2.4 Compensation techniques

The transmission of the optical signal through the optical cable gets effected by several kinds of losses which can be mitigated or compensated by several techniques.

2.4.1 Optical amplifiers

The launched power to the fiber is not constant during the transmission distance. It gets attenuated due to the attenuation losses that have been studied in the previous parts. While at the receiver, the minimum power required to achieve a certain BER of 10^{-9}. Optical amplifiers are devices that have been invented to directly amplify (boost) the optical data signal without changing it into its electrical form. Optical amplifiers are used repeatedly whenever the optical signal achieves the minimum allowed power to boost it back to its initial power, as shown in figure 2.7. [7]

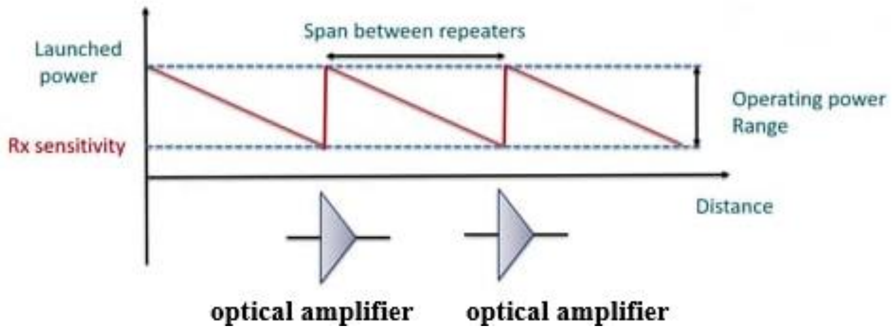


Figure 2.7 Multiple power amplifications

The optical amplifier is connected to an optical or an electrical pump. It can be used to amplify multiple channels in WDM systems linearly. It is independent of bit rate and modulation format. The major optical amplifiers are: erbium doped fiber amplifiers (EDFA), Raman amplifiers (RA) that are connected to optical pumps, and semiconductor optical amplifiers (SOA) connected to electrical pump. Figure 2.8 represents an optical amplifier with a pump.

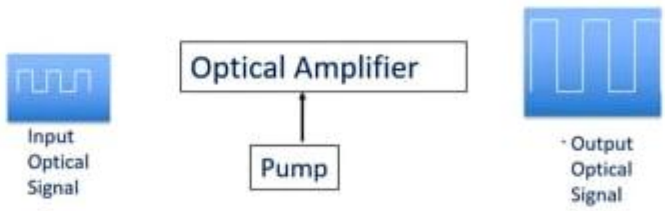


Figure 2.8 Optical amplifier

2.4.2 Dispersion compensation techniques

The different types of dispersion can be compensated by different techniques that depends on the type of dispersion and on the technology used for compensation.

2.4.2.1 Polarization mode dispersion compensation techniques

Polarization dispersion can be compensated by at least two methods; delay method and phase shift method as shown in figure 2.9 and in figure 2.10.

a. Delay method

This technique is based on a delay line between the two components of the electromagnetic wave along the two axes at its initial state called principle state of polarization (PSP). The polarization controller and the beam splitter separate the signal into two along the PSP. The component having the highest speed is delayed by using variable delay in its branch. Finally, polarization combiner is added to combine the two components together. [12]

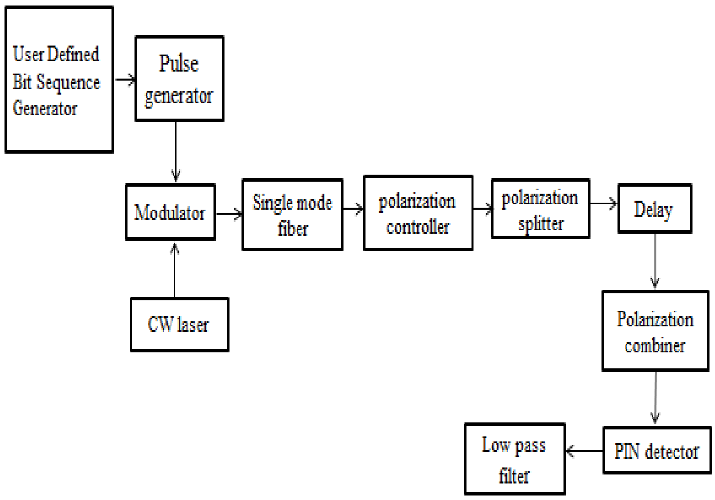


Figure 2.9 Model for delay method [12]

b. Phase shift method

Phase shift technique is based on polarization rotator, which is a device that rotates the state of polarization (SOP) of the signal from the fiber with different angles. The variation in the angle causes an adjustable delay. Hence, the polarization distortion can be compensated. [12]

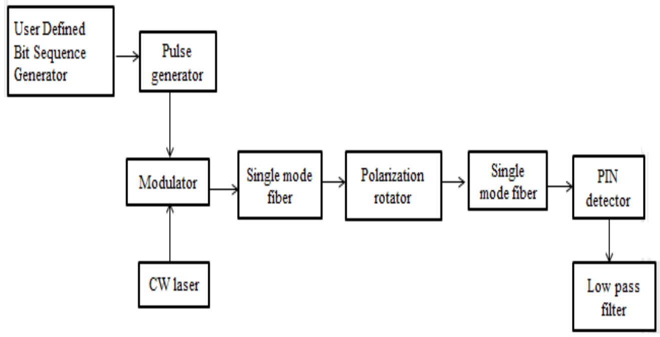


Figure 2.10 Model for phase shift method [12]

2.4.2.2 Chromatic dispersion compensation techniques

a. Dispersion compensating fiber (DCF)

DCF is the most common dispersion compensation technique, used for long distance communication, it is a loop of fiber relatively short in length comparing to the length of the transmission fiber. It has high values of negative dispersion -70 to -90 ps/nm.km related to the dispersion of the transmitting fiber by the following equation:

$$D_{SMF} \times L_{SMF} = -D_{DCF} \times L_{DCF} \qquad (2.1)$$

D_{SMF} : Dispersion of single mode transmission fiber

L_{SMF} : Length of single mode transmission fiber

D_{DCF} : Dispersion of DCF

L_{DCF} : Length of DCF

According to equation (2.1) the dispersion in the DCF nullifies the total dispersion. [13]

Figure 2.11 shows the role of a DCF compensator.

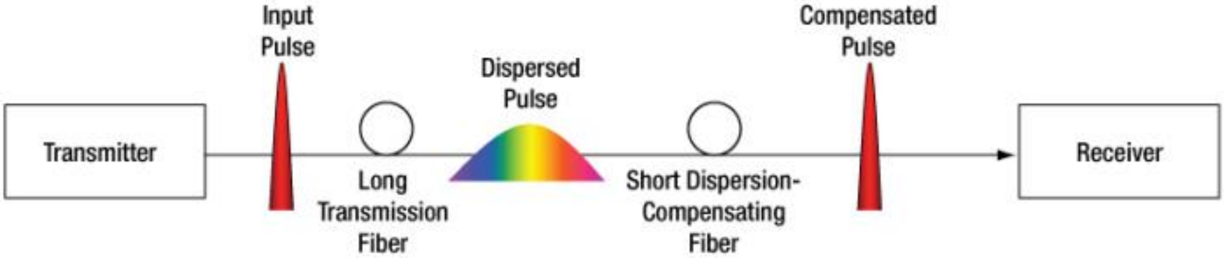


Figure 2.11 DCF compensator [22]

b. Fiber Bragg grating (FBG)

The fiber Bragg grating is a device that is used for many applications in the optical communication, one of these applications is the chromatic dispersion compensation. Chromatic dispersion is caused by the delayed low frequencies wavelengths, while the FBG chirp is designed to reject the higher frequencies such that the chromatic dispersion gets cancelled, as illustrated in figure 2.12.

It is an optical fiber section in which the refractive index of the core changes periodically along its length. FBG works as an optical filter that rejects a band centered at the Bragg wavelength λ_B , where the incident light is reflected back. The Bragg wavelength is related to the grating period Λ, by $\lambda_B = 2n_e\Lambda$, where n_e is the effective refractive index of the FBG core. [14]

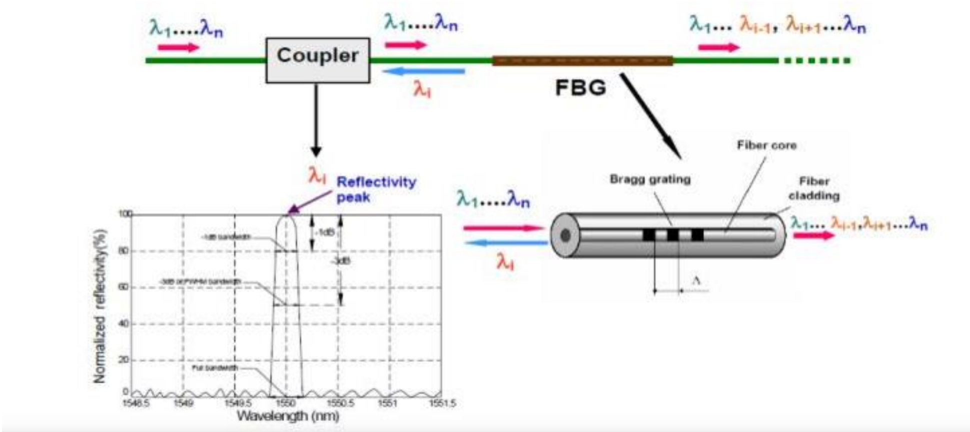


Figure 2.12 FBG compensator [24]

c. Optical phase conjugation technique

Optical phase conjugation technique is based on a device, which acts as a mirror. It is placed in the middle of the transmission link. It reverses the propagation direction and the phase variation so that the dispersion accumulated is the first half gets compensated by conjugation, while passing through the next half of the transmission link.

Note: All types of dispersion and nonlinear losses can be mitigated by the use of electronic dispersion compensators (EDC) that compensate the electrical signal after detection or by the use of digital filters.

Conclusion

In this chapter, technologies for attenuation and dispersion compensation have been explained, so that the quality of transmission is enhanced. The two famous techniques of dispersion compensation: fiber Bragg grating and dispersion compensation fiber are chosen to be studied and compared to each other, in the next chapter.

Chapter 03
Simulation and results

3.1 Introduction

In this chapter, different systems are designed and simulated. First, a 4-Channel WDM system is simulated for different transmission distances, in different transmission rates and input power injections, without dispersion compensation. Then, DCF and FBG compensation techniques are added to the system for transmission distance of 90Km, and their effect is analyzed for different bit rates and input power. Then, the effect of FBG and DCF compensators on an 8-Channel WDM system is analyzed. Finally, multistage FBG and DCF techniques are introduced for a 2-Channel WDM system.

3.2 Presentation of the OptiSystem Software

Optisystem software is an advanced optical communication system simulation package. It is set for designing, optimizing, and testing any category of optical link in the physical layer of the broad spectrum for optical networks, from Long-Haul Networks, Metropolitan Area Networks (MANs) and Local Area Networks (LANs). It can support operators to design experiments and simulate many applications, such as CATV or WDM/TDM or networks, dispersion map plans, transmitters, receivers, and amplifier designs. It is a system level simulator based on the realistic modeling of fiber-optic communication systems. OptiSystem possesses a powerful simulation environment and a truly hierarchical definition of components and systems. [15]

The OptiSystem main window is represented in Figure 3.1.

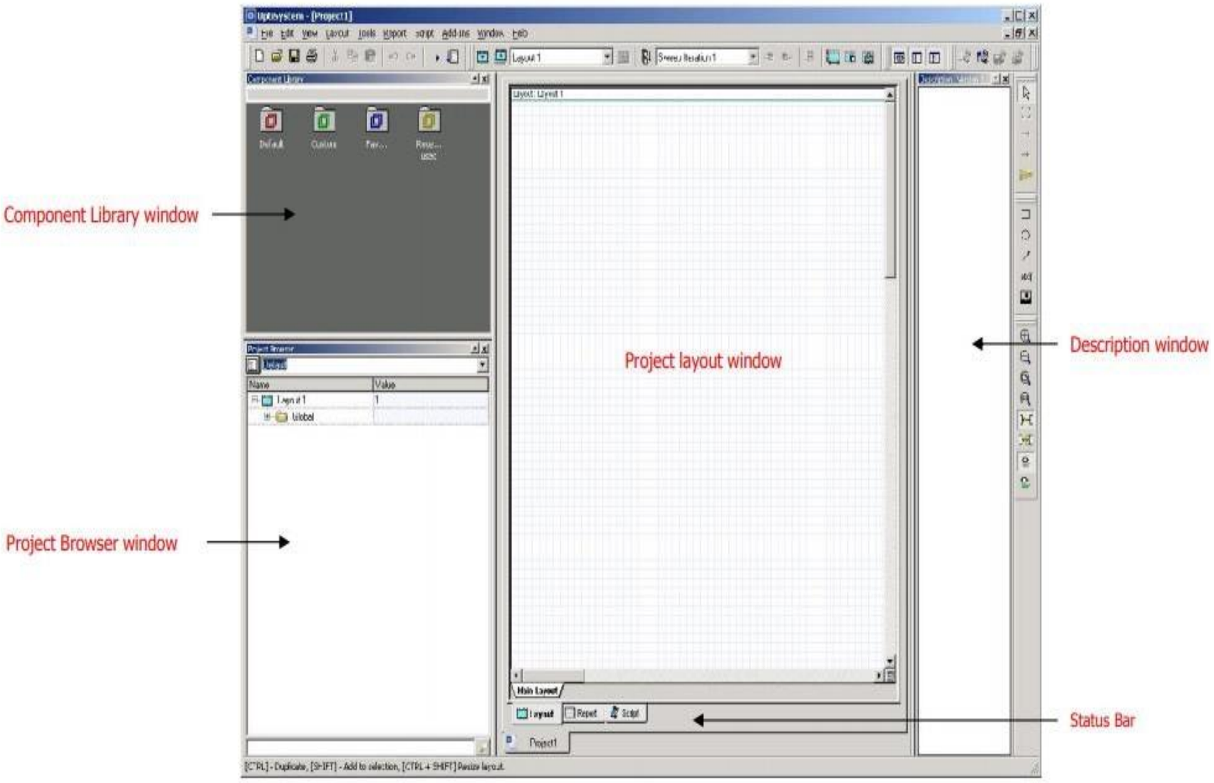


Figure 3.1 OptiSystem graphical user interface [26]

To carry out project simulations, OptiSystem-Optiwave version7.0 is used.

3.3 Simulation setup

This section describes the simulation setup in the OptiSystem software, and the parameters used for different configurations.

3.3.1 The transmitter structure

The WDM transmitter bloc consists of pseudo random bit sequence generator that generates bits at different bit rates, shown in table 3.1, coded by a NRZ pulse generator, CW laser having power of 10dBm and Mach-Zehnder modulator. At a frequency of 193.1 THz. As shown in figure 3.2.

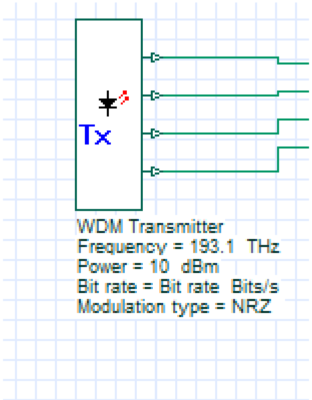


Figure 3.2 The transmitter model

3.3.2 The transmission lines

Different configurations of transmission lines are used. The main transmission line of this WDM system consists of a WDM MUX (with different numbers of channels through the simulation process), an optical amplifier of 7dB power gain, a single mode optical fiber (different length are used), another optical amplifier of 7dB power gain, a WDM DEMUX (with different numbers of channels through the simulation process) , as seen in Figure 3.3.

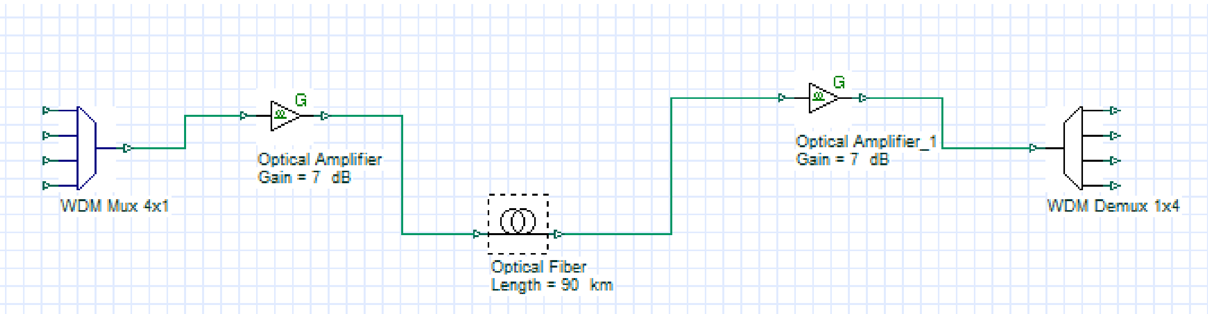


Figure 3.3 The main transmission line model

During the simulation process, Ideal Dispersion Compensation FBG chirps and Dispersion Compensation Fibers (DCFs) are added in several configurations.

3.3.3 The receiver structure

The receiver consists of a Photodetector, a Low Pass Bessel Filter, connected to a 3R Regenerator and a BER Analyzer to evaluate the system Q factor, BER and obtain the eye diagram. The receiver structure is shown in Figure 3.4.

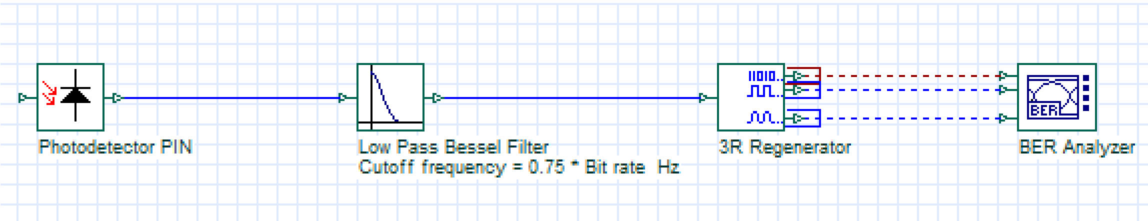


Figure 3.4 The receiver model

3.4 Simulation and results discussion

In this section, Simulations are done without dispersion compensation and then with using two different dispersion compensation techniques. First, using FBG technique then, using DCF technique. Finally, the two techniques are compared two each other.

3.4.1 Simulation without dispersion compensation

A 4-Channel WDM system is simulated for different optical fiber lengths at different bit rates and for different input power values. Figure 3.5, Figure 3.6 and Figure 3.7 show the uncompensated systems.

The different parameters of the system are listed in Table 3.1.

Table 3.1 The system parameters

Parameter	Value
Bit Rate (Gbits/s)	3, 6, 9, 12, 15
Laser Power (dBm)	-10, -5, 0, 5, 10, 15
Length of SMF (km)	60, 90, 120
Length of DCF(km)	9, 18
Dispersion coefficient of SMF (ps/nm/km)	16.75
Dispersion coefficient of DCF (ps/nm/km)	-83.75
Gain of optical amplifier (dB)	7
FBG Apodization function	Tanh (parameter 4)
Linear parameter (μm)	0.0001
Length (mm)	10
Frequency (Thz)	193.1
Frequency spacing (Ghz)	100

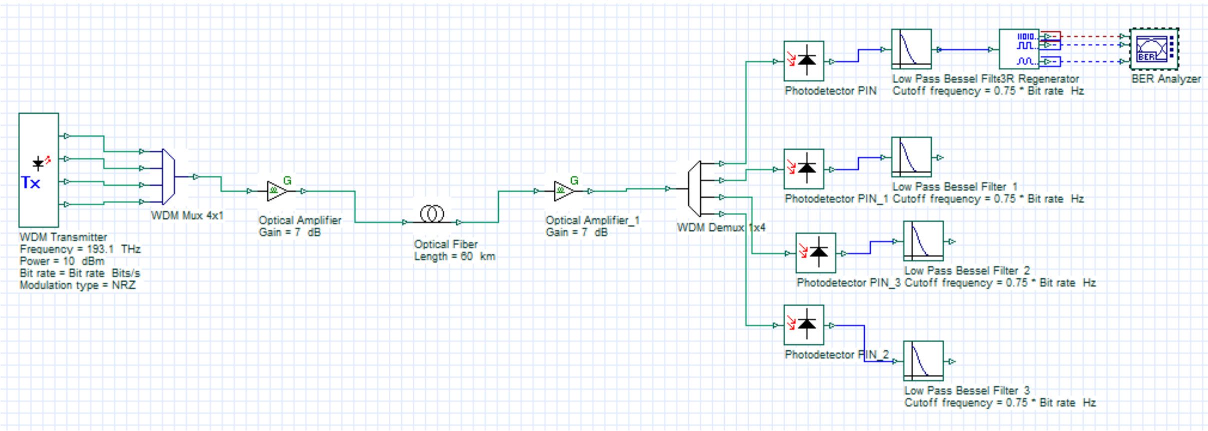


Figure 3.5 4-Channel WDM system of 60Km optical fiber length

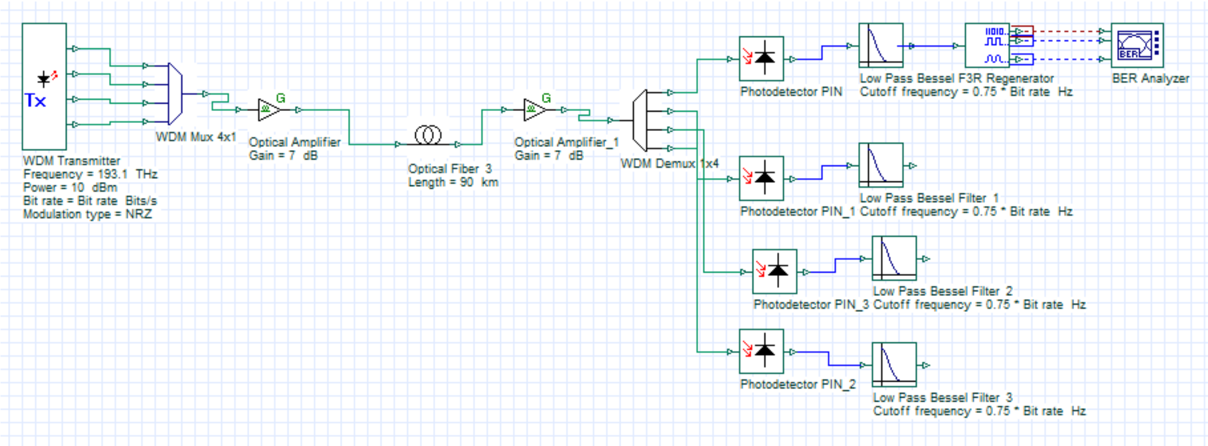


Figure 3.6 4-Channel WDM system of 90Km optical fiber length

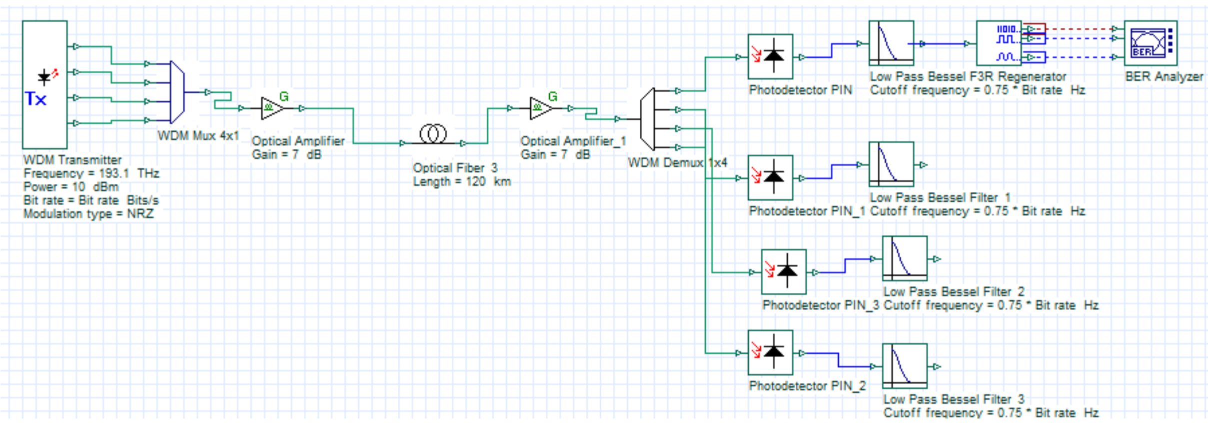
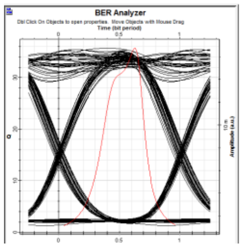
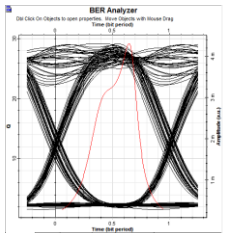
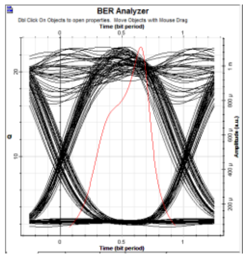
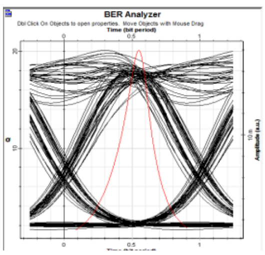
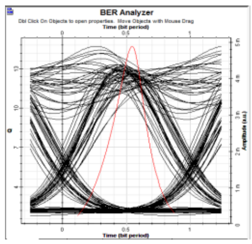
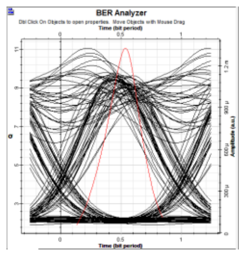
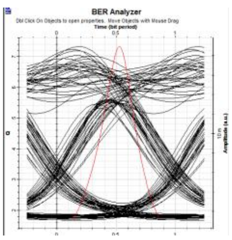
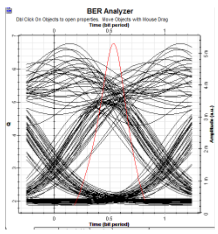
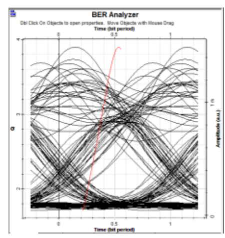


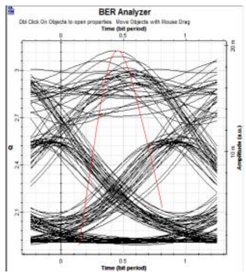
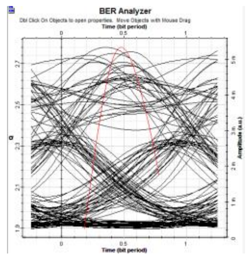
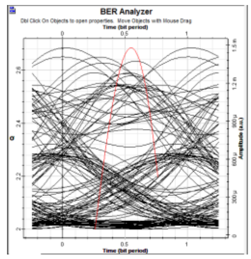
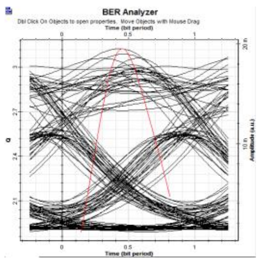
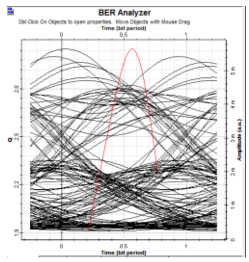
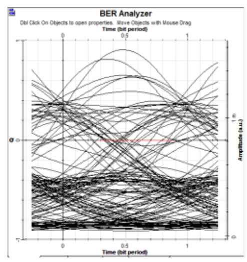
Figure 3.7 4-Channel WDM system of 120Km optical fiber length

3.4.1.1 Effect of bite rate and distance variation on Q factor

The simulation results for different transmission rates at input power of 10dBm, obtained from channel-1 are shown in Table3.2.

Table 3.2 Eye diagrams and Q factors for different bit rates at input power of 10dBm for 60Km, 90Km and 120Km

Distance (Km) / Bit rate (GBit/S)	60	90	120
Eye diagram at 3GBit/s			
Q factor at 3GBit/s	36.6742	29.1816	22.93333
Eye diagram at 6GBit/s			
Q factor at 6GBit/s	20.1140	14.7071	11.0600
Eye diagram at 9GBit/s			
Q factor at 9GBit/s	7.3174	6.7671	3.8944

Eye diagram at 12GBit/s			
Q factor at 12GBit/s	3.1250	2.7790	2.6836
Eye diagram at 15GBit/s			
Q factor at 15GBit/s	3.1250	3.0488	0

The resulted Q factors versus bit rates from Table3.2, are represented in a graph, in Figure3.8.

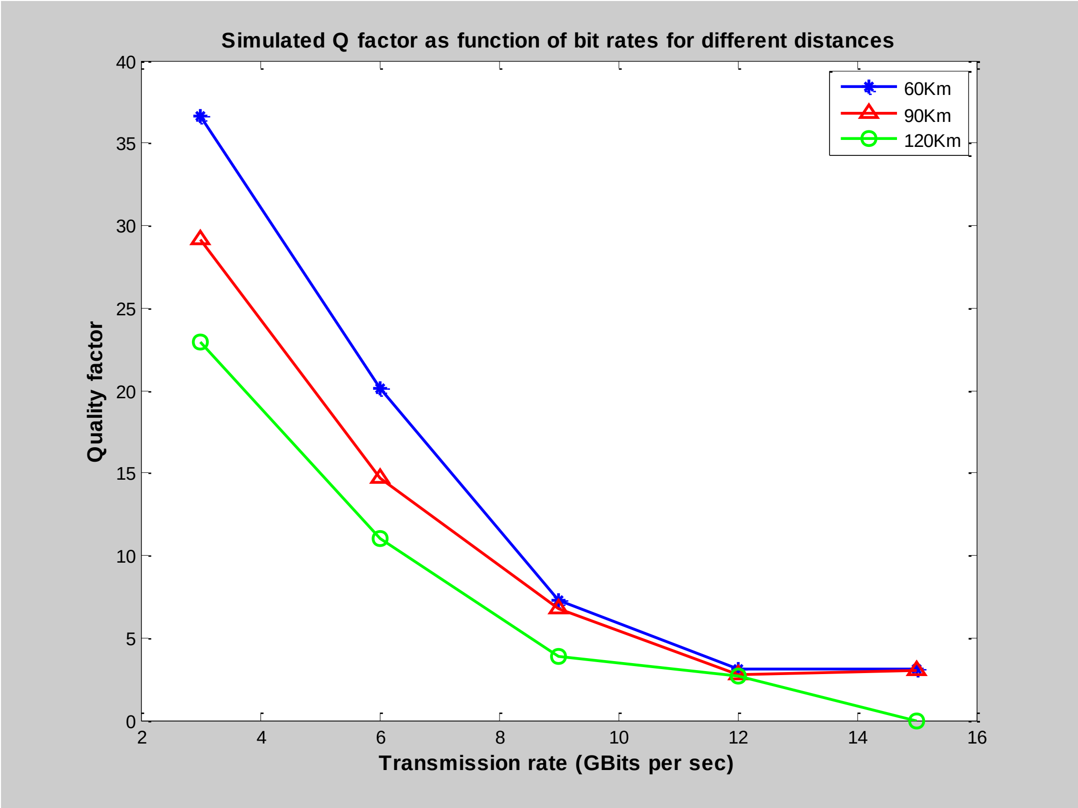


Figure 3.8 Simulated Q factor versus bit rates for different distances at Pin=10dBm

From table 3.2, it is observed that for each distance, whenever the bit rate increases, the eye diagrams degrade, and show bad eye opening. And for each bit rate, whenever the distance increases the eye diagrams are closing and show bad results too.

From figure 3.8, it is clear that the Q factor is decreasing for every increase in the bit rate or in the optical fiber transmitted distance.

It can be concluded that when the transmission rate or the transmission distance increases, the dispersion gets bigger causing Q factor and eye diagram degradation.

3.4.1.2 Effect of input power and distance variation on Q factor

The simulation results for different values of input power at transmission rate of 6GBit/s, obtained from channel-1 are shown in Table3.3.

Table 3.3 Q factors for different input power values at transmission rate 6GBit/s for 60Km, 90Km and 120Km

SMF length (Km) / Input power (dBm)	60	90	120
-10	15.0565	10.3447	3.8801
-5	15.9334	13.6059	7.8935
0	17.6416	15.6970	11.6599
5	22.4233	21.7471	17.6599
10	20.1140	14.7071	11.0600
15	3.1055	2.5237	2.9882

The corresponding graph of table 3.3 is shown in figure 3.9.

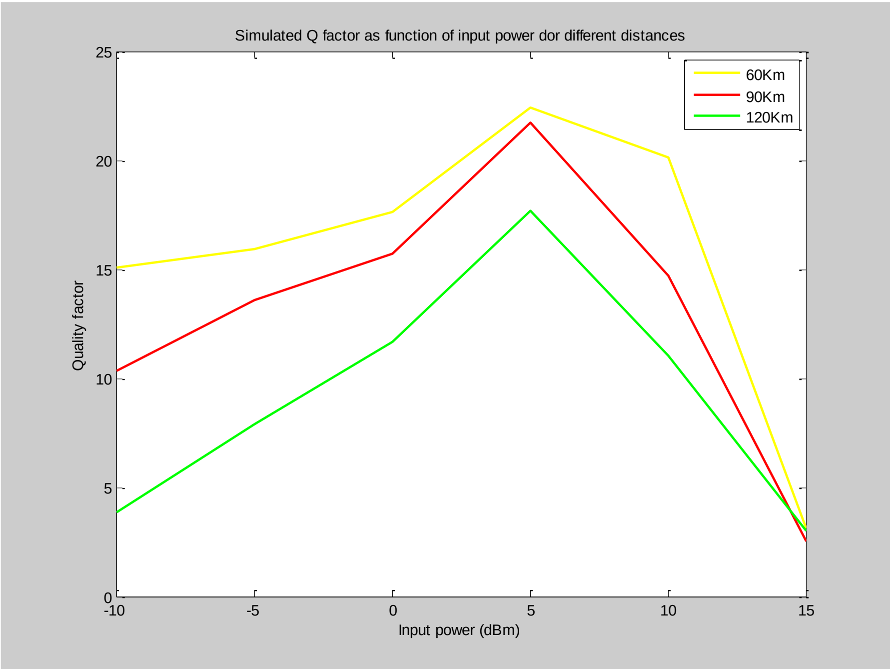


Figure 3.9 Simulated Q factor versus input power for different distances at 6GBit/s

From figure 3.9, it is clearly observed that the Q factor increases whenever the input power increases in the interval [-10,5]dBm. However, in the interval [10,15]dBm the Q factor decreases for every increase in the input power and it is very low at 15dBm. It is also noticed that whatever is the value of the input power, the Q factor is lower for bigger distances.

At the interval [-10,5]dBm, the increase of power insure a good data transmission and reduces the dispersion. But, when the power keeps increasing (at 10dBm and more) the problem of nonlinearities starts to appear, causing low Q factors and bad eye diagrams. The eye diagrams for Pin=15dBm at 6GBit/s are shown in figure 3.10.

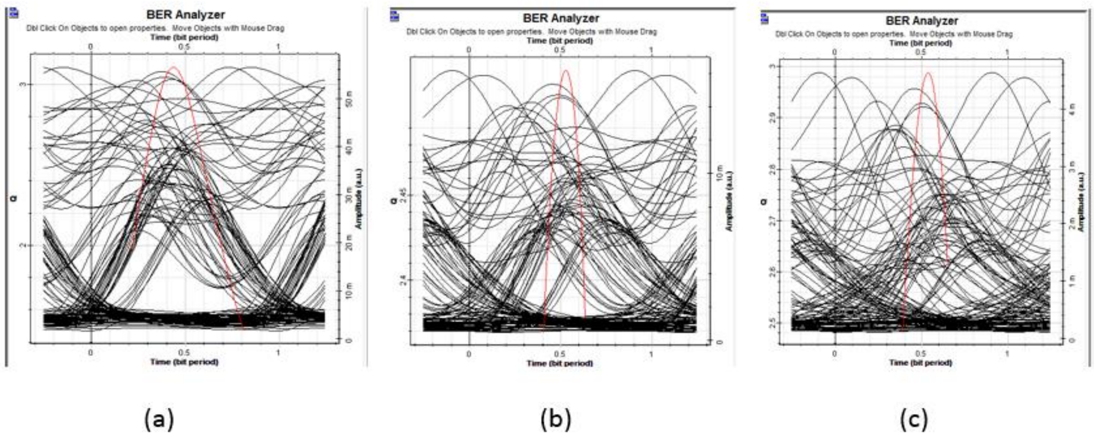


Figure 3.10 Eye diagram for Pin=15dBm at 6GBit/s (a)60Km (b)90Km (c)120Km

3.4.2 DCF and FBG dispersion compensators added to the system

The 4-channel WDM system of the previous section with the corresponding parameters shown in table 3.1 is used at 90 Km distance. For different transmission rates and input powers.

The different DCF and FBG configurations are shown in figure 3.11 and figure 3.12.

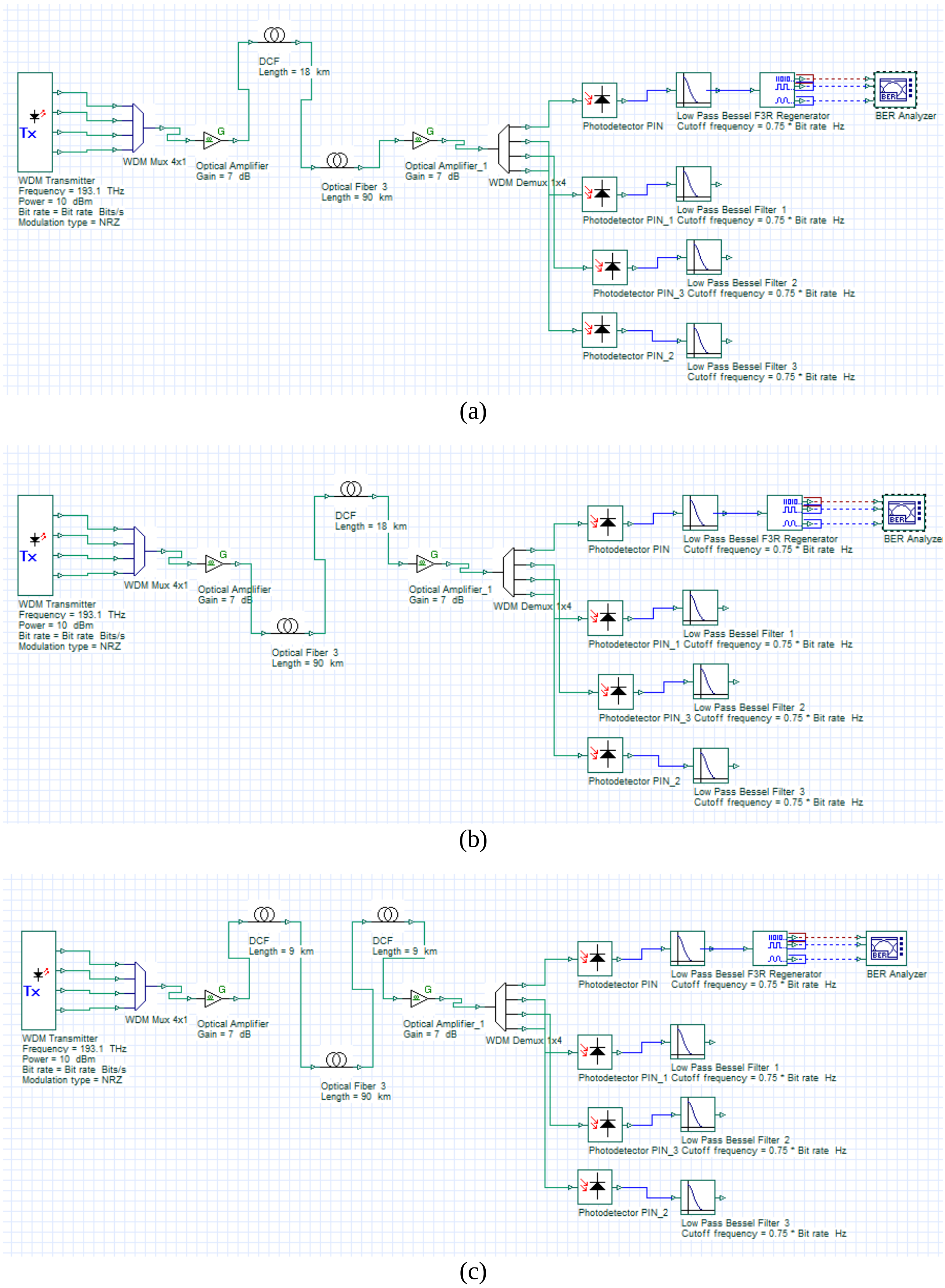
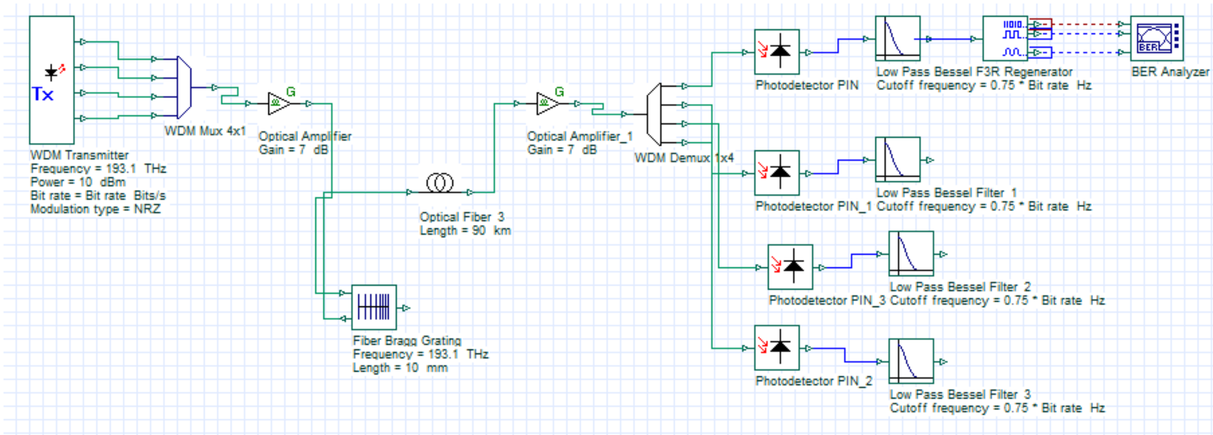
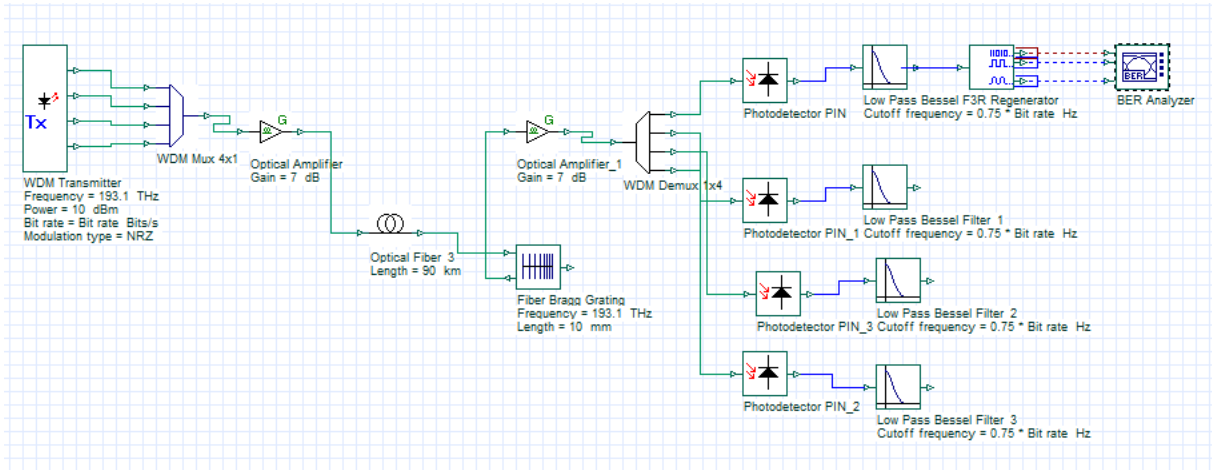


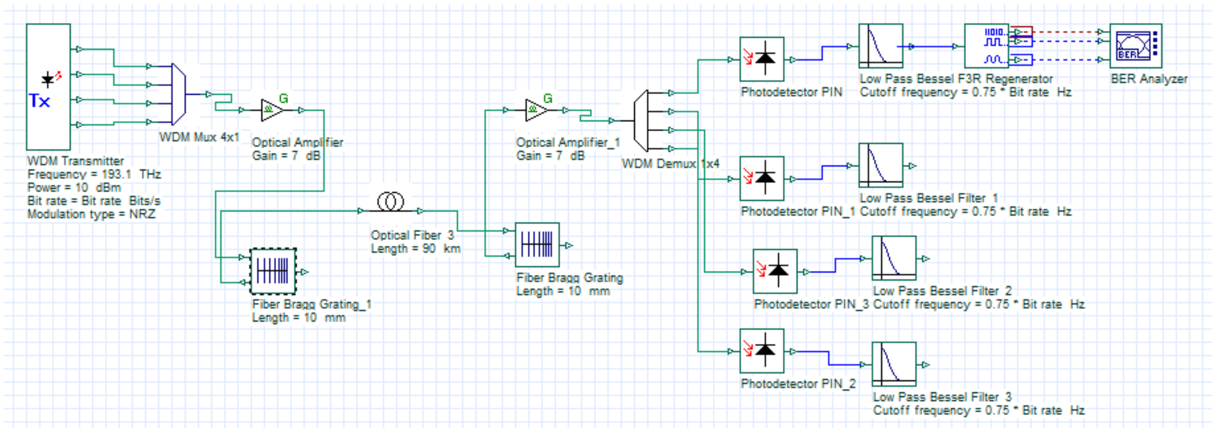
Figure 3.11 Dispersion compensation design using DCF (a) Pre-compensation, (b) Post-compensation, (c) Symmetric compensation



(a)



(b)



(c)

Figure 3.12 Dispersion compensation design using FBG (a) Pre-compensation, (b) Post-compensation, (c) Symmetric compensation

3.4.2.1 DCF and FBG compensation techniques for different transmission rates

Dispersion compensation techniques FBG and DCF in different configurations are added to the system at input power of 10dBm, for different transmission rates as in table 3.4.

Table 3.4 Q factor results for both FBG and DCF configurations at Pin=10dBm for different transmission rates

Bit rates(GBit/s)	**DCF**			**FBG**		
	Pre	Post	Symmetric	Pre	Post	Symmetric
3	40.0478	44.5719	44.9025	77.9419	30.6660	93.0737
6	21.6750	8.5954	20.0173	47.9800	16.7465	41.8811
9	8.5183	3.5248	7.3448	9.0230	6.5619	7.6986
12	3.7798	2.2423	4.0624	3.9254	3.0838	4.3366
15	3.6689	2.3448	3.6679	4.3902	3.1881	4.2709

The data of table 3.4 are in graphical representation, in figure 3.13.

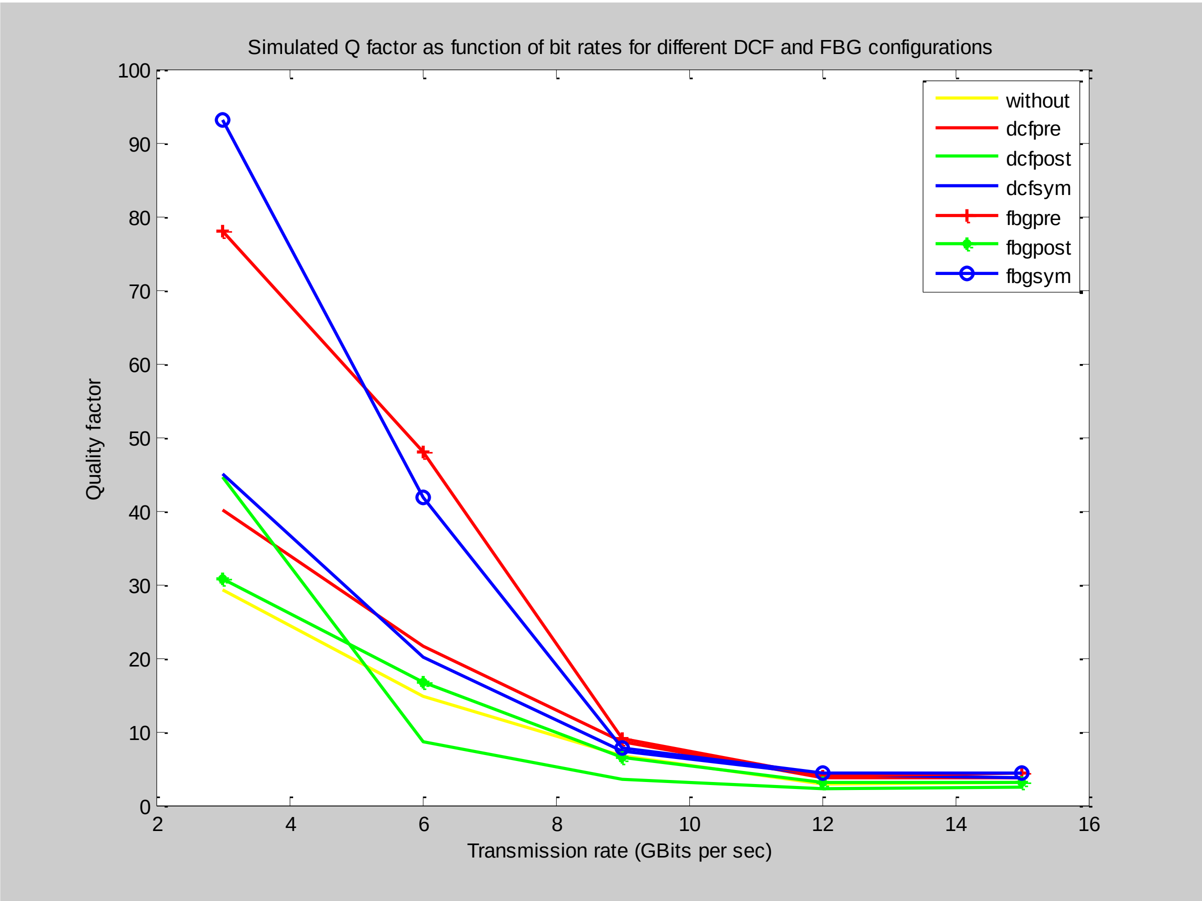


Figure 3.13 Q factor versus transmission rates for DCF and FBG compensation configurations

From figure 3.13, it is clear that the Q factor results of FBG post-compensation technique are very similar to the ones of the uncompensated system. The resulted Q factor of DCF post-compensation technique is better than the resulted Q factor of the uncompensated system at 3GBit/s then it gets lower than it causing a degradation in the system performance.

DCF pre-compensation and symmetric compensation techniques give clearly better resulted Q factors than the uncompensated system. However, they show approximately the same results at higher rates.

FBG pre-compensation and symmetric compensation techniques result very high Q factors and enhance the system performance. However, for higher transmission rates they are similar to the uncompensated system.

In general, in the interval [3,9]GBit/s, DCF and FBG pre-compensation and symmetric compensation techniques compensate the dispersion and enhance the system clearly. However, FBG techniques are the best.

3.4.2.2 DCF and FBG compensation techniques for different input power

Dispersion compensation techniques FBG and DCF in different configurations are added to the system at transmission rate of 6GBit/s, for different input power as represented in table 3.5.

Table 3.5 Q factor results for both FBG and DCF configurations at transmission rate 6GBit/s for different input power values

Input power (dBm)	**DCF**			**FBG**		
	Pre	Post	Symmetric	Pre	Post	Symmetric
-10	6.4358	6.3986	6.4325	8.3246	8.3137	7.1531
-5	13.7951	13.3958	13.6069	12.5207	12.5634	11.7909
0	20.7704	17.0931	19.5782	14.5578	14.9396	13.8637
5	31.1740	15.2798	23.7514	19.6491	20.1923	17.4675
10	21.6750	8.5954	20.0173	47.9800	16.7465	41.8811
15	4.8115	3.5390	3.7283	22.6246	2.4794	12.7265

The data in table 3.5 are graphically represented in Figure 3.14.

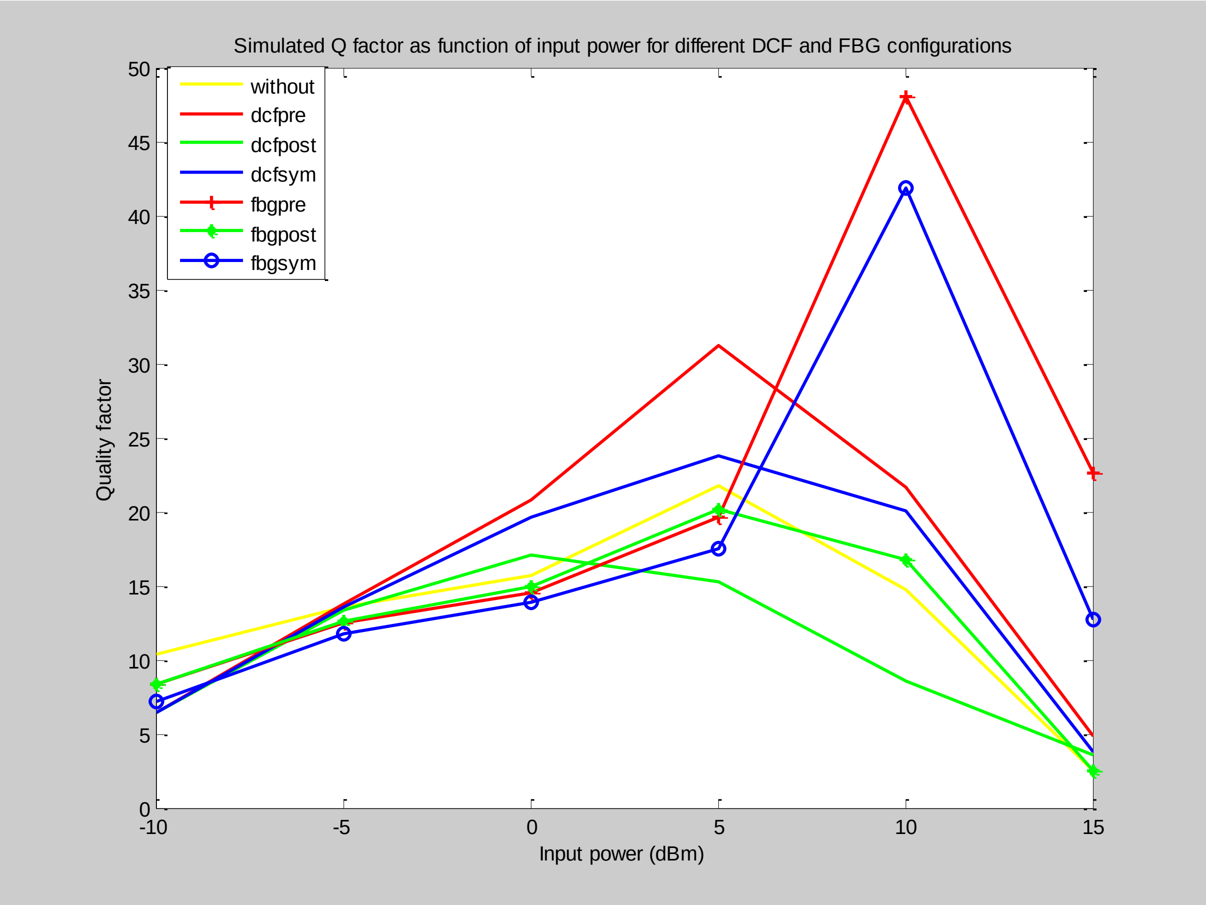


Figure 3.14 Q factor versus input power for DCF and FBG compensation configurations

From figure 3.14, It is observed that in the interval [-10,-5] the system without dispersion compensation has better Q factor results than the compensated ones. In the interval [-5,15] DCF pre-compensation and symmetric compensation techniques show slightly better Q factors than the uncompensated system.

At 10dBm , the uncompensated system performance degrades because of the nonlinearities, but FBG pre- compensation and symmetric compensation techniques give peaks of Q factor results and high performance to the system and they keep having good Q factors at 15dBm input power. Which means that the FBG technique (pre-compensation and symmetric compensation) compensate the nonlinearities in the system.

FBG and DCF post-compensation techniques do not show any interesting results.

It can be concluded that for considerable low input power the system has good performance and does not need any dispersion compensation then, when the power keeps increasing the DCF compensation techniques give better results and enhance the system performance, till the increase in power creates nonlinearities problem that can be mitigated by the FBG compensation techniques.

3.4.3 Effect of FBG and DCF compensators on 8-channel WDM system

Parameters of the system are shown in table 3.6.

Table 3.6 The system parameters

Parameter	Value
Bit Rate (Gbits/s)	5
Laser Power (dBm)	10
Length of SMF (km)	60
Length of DCF(km)	6, 12
Dispersion coefficient of SMF (ps/nm/km)	16.75
Dispersion coefficient of DCF (ps/nm/km)	-83.75
Gain of optical amplifier (dB)	6
FBG (Uniform) Bandwidth(THz)	1
Frequency (Thz)	193.1
Frequency spacing (Ghz)	100

8-channel WDM system has been designed according to the parameters of table 3.6.

First the system is designed and simulated without any dispersion compensator added to it, then DCF compensator is added in its different configurations; pre-compensation, post-compensation and symmetric compensation. Finally, FBG is added to the uncompensated system in its different configurations; pre-compensation, post-compensation and symmetric compensation. The results of these different techniques are represented in table 3.7, table 3.8 and table 3.9.

Figure 3.15 shows the 8-channel WDM system design.

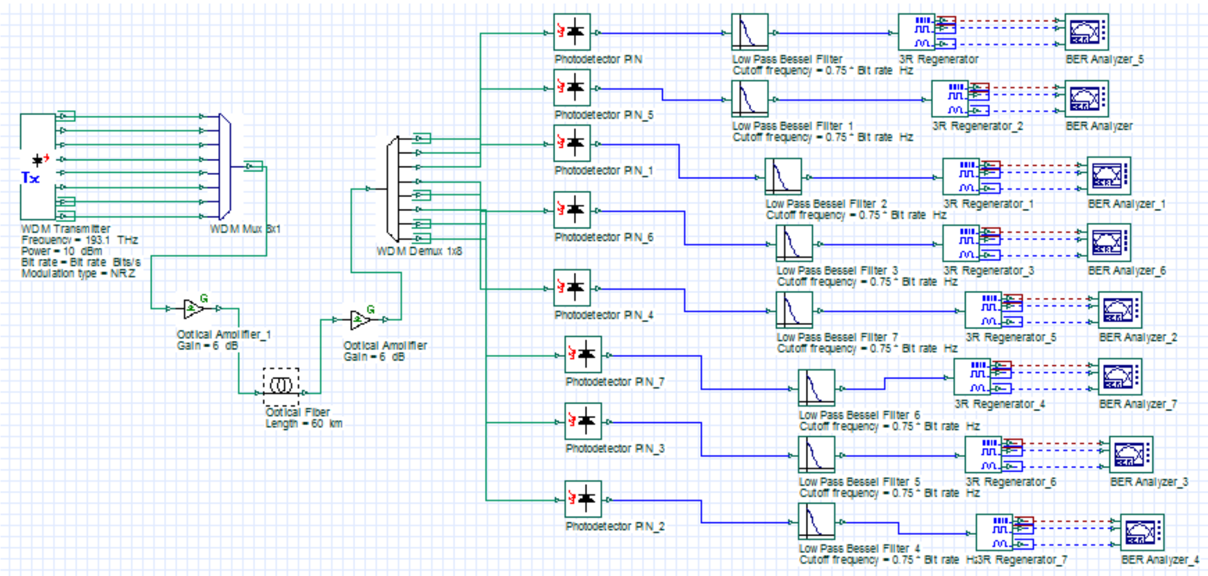


Figure 3.15 8-channel WDM system design

Table 3.7 Eye diagrams and Q factors resulted from the system without dispersion compensation

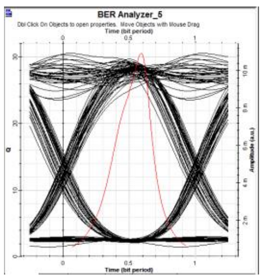
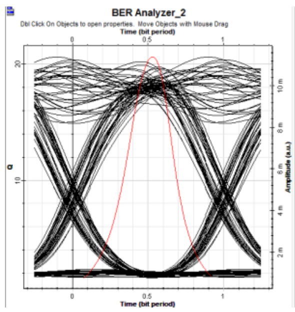
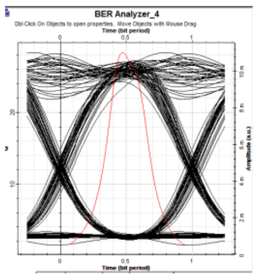
Uncompensated system	**Channel 1**	**Channel 5**	**Channel 8**
Eye diagram			
Q factor	30.5303	20.6279	28.3465

Table 3.8 Eye diagrams and Q factors resulted from the system with DCF dispersion compensation techniques

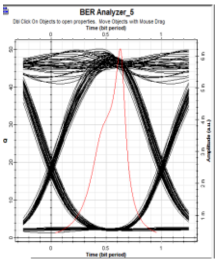
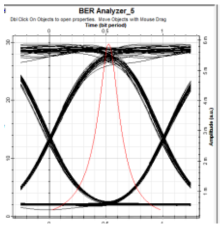
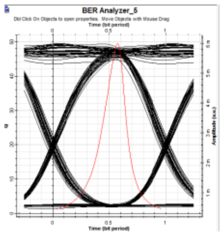
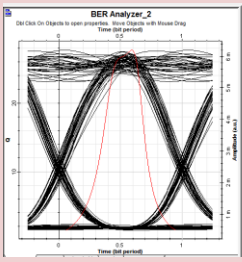
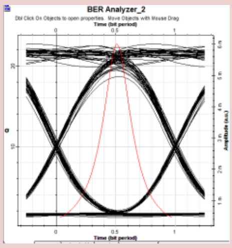
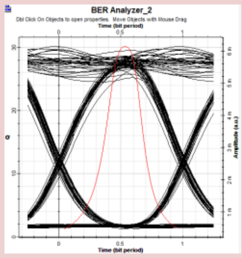
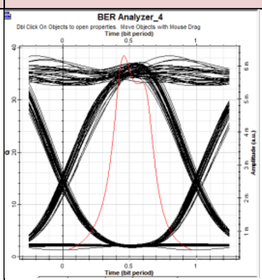
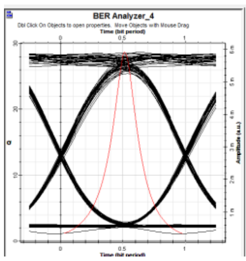
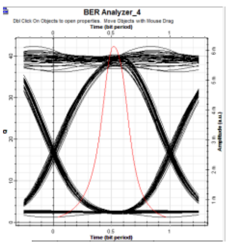
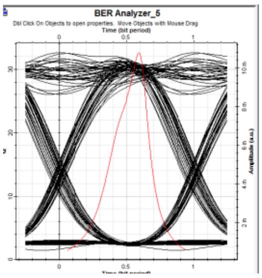
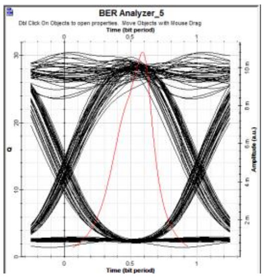
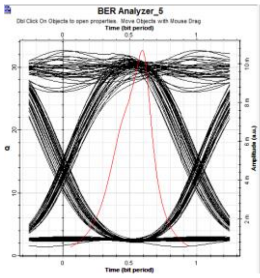
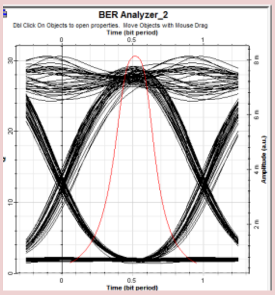
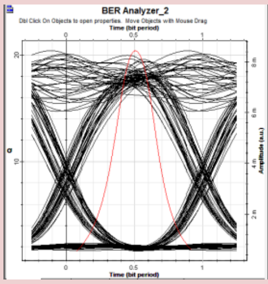
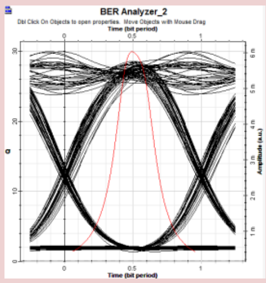
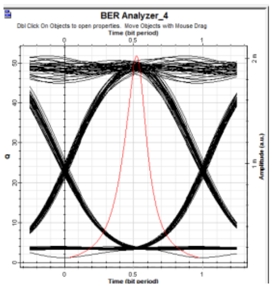
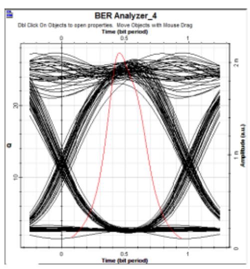
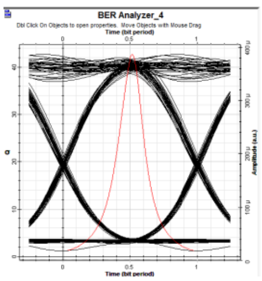
Number of channel	**DCF**		
	Pre	Post	Symmetric
Channel 1 Eye diagram			
Q factor	50.0920	29.6672	49.4757
Channel 5 Eye diagram			
Q factor	27.7106	22.7208	30.1590
Channel 8 Eye diagram			
Q factor	38.4267	28.6591	42.2802

Table 3.9 Eye diagrams and Q factors resulted from the system with FBG dispersion compensation techniques

Number of channel	**FBG**		
	Pre	Post	Symmetric
Channel 1 Eye diagram			
Q factor	32.5979	30.4913	32.6768
Channel 5 Eye diagram			
Q factor	30.5951	20.3904	29.9446
Channel 8 Eye diagram			
Q factor	51.8082	27.3144	42.6988

It is seen from table 3.7 that the Q factors and eye diagrams of the system without dispersion compensation for channel 1 and channel 8 are slightly better than the ones for channel 5.

In table 3.8, DCF dispersion compensation techniques are added to the system. For DCF pre-compensation technique and symmetric compensation technique, the system channels 1, 5 and 8 are enhanced and shows much greater Q factors and more open and high eye diagrams. While DCF post-compensation technique does not show a very big enhancement and the resulted Q factors and eye diagrams are approximately similar to the ones of the system without dispersion compensation.

In table 3.9, FBG dispersion compensation techniques are added to the system. FBG pre-compensation and symmetric compensation techniques show an enhancement in channel 1, 5 and 8 of the system, the eye diagrams are very open and the Q factors are very large than the ones of the uncompensated system. While the FBG post-compensation technique does not have any effect on the system performance and the Q factors for channels 1, 5 and 8 do not change in a noticeable way.

It is concluded that DCF compensation techniques are effecting the system in a similar manner to FBG compensation techniques. The Q factors and eye diagrams in FBG techniques do not show a big difference than those of DCF techniques for 8-Channel WDM system. DCF and FBG pre-compensation and symmetric compensation techniques are the best techniques that enhance the system performance. While the post-compensation techniques do not result any enhancement in the 8-channel WDM system.

3.4.4 Multistage DCF and FBG in 2-channel WDM system

The parameters of the system are shown in table 3.10.

Table 3.10 2-channel WDM system parameters

Parameter	Value
Bit Rate (Gbits/s)	6
Laser Power (dBm)	10
Length of SMF (km)	60, 120
Length of DCF(km)	12, 24
Dispersion coefficient of SMF (ps/nm/km)	16.75
Dispersion coefficient of DCF (ps/nm/km)	-83.75
Gain of optical amplifier (dB)	7
IDCFBG Bandwidth(THz)	1
Frequency (Thz)	193.1
Frequency spacing (Ghz)	100
Dispersion of IDCFBG (ps/nm)	-800

The 2-channel WDM system is designed and simulated without dispersion compensation, then FBG and DCF dispersion compensators are added to the system in one stage (Pre-compensation technique) and finally in two stages. The system designs are shown in figure 3.16, figure 3.17, and figure 3.18.

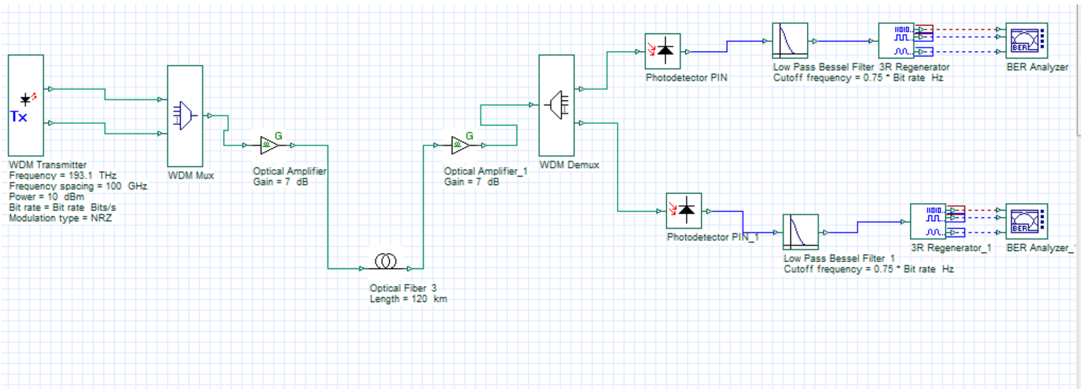
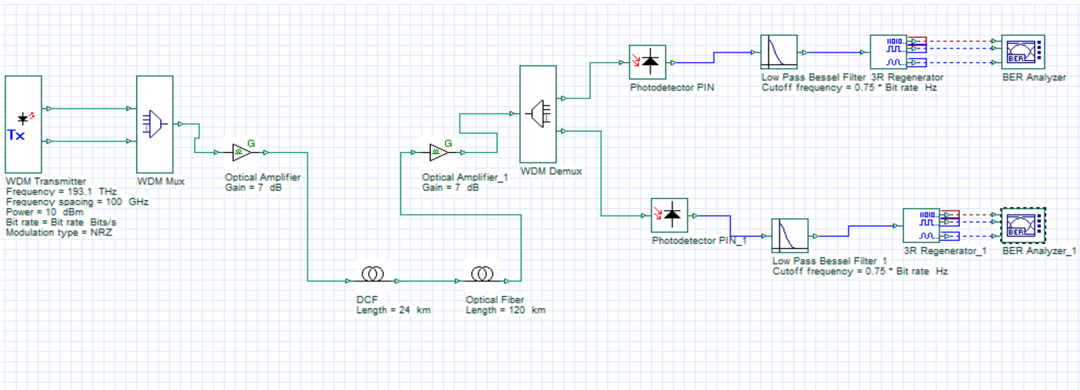
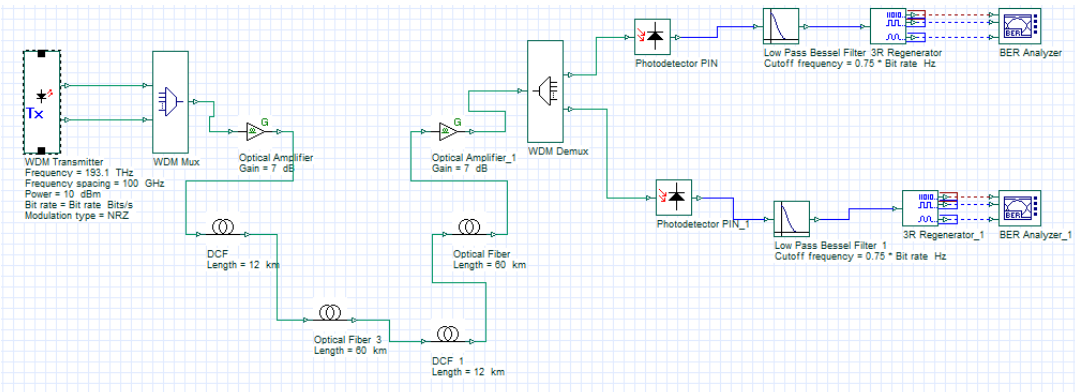


Figure 3.16 2-Channel WDM system

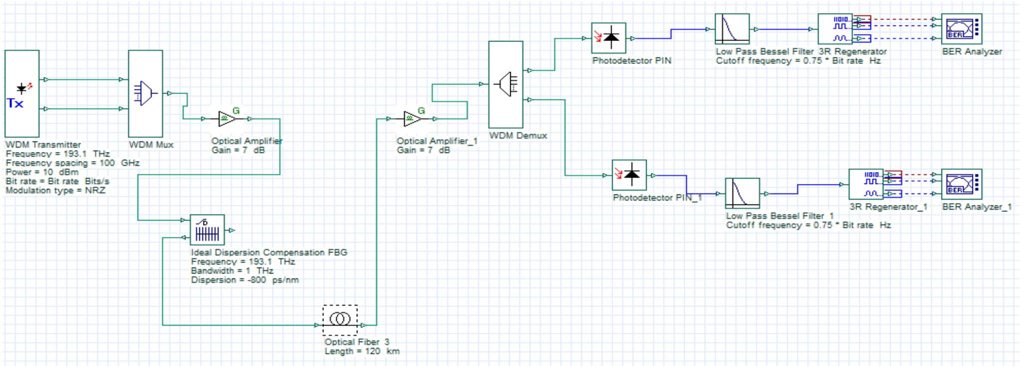


(a)

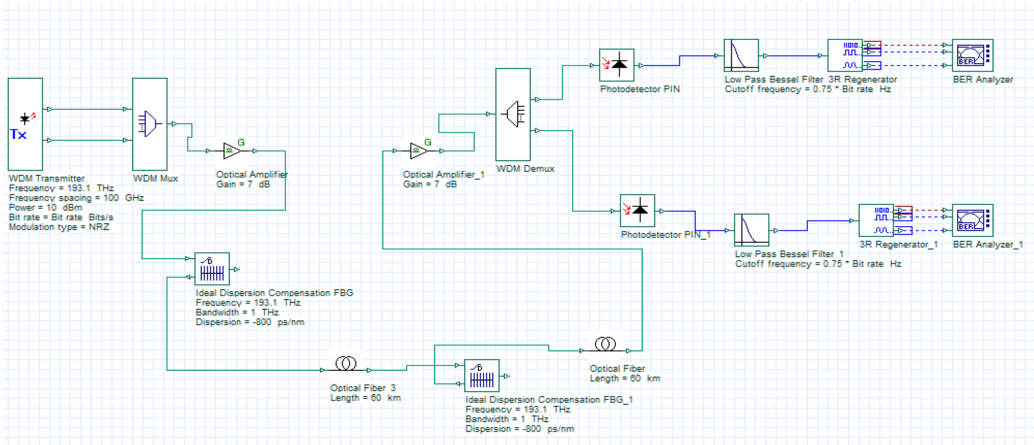


(b)

Figure 3.17 2-Channel WDM system with DCF compensation technique (a) 1-stage technique, (b) 2-stage technique



(a)

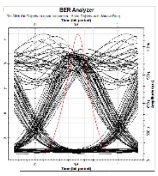
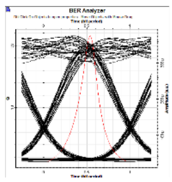
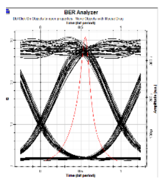
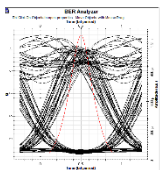
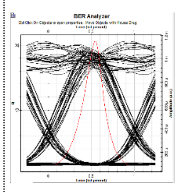
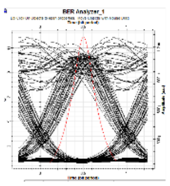
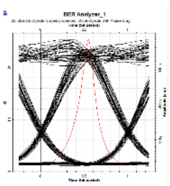
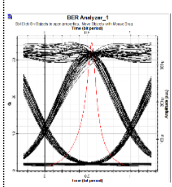
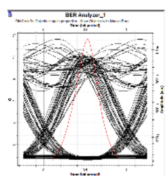
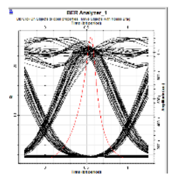


(b)

Figure 3.18 2-Channel WDM system with FBG compensation technique (a) 1-stage technique, (b) 2-stage technique

The resulted Q factors and eye diagrams from all the previous techniques are shown in table 3.11.

Table 3.11 Q factors and eye diagrams resulted from DCF and FBG 1-stage and 2-stage compensation techniques

	System without compensation	DCF		FBG	
		1-stage	2-stages	1-stage	2-stages
Channel 1 Eye diagram					
Q factor	11.3794	21.5825	30.7115	12.1561	20.6056
Channel 2 Eye diagram					
Q factor	11.8775	25.2963	34.7923	12.6527	25.8474

From table 3.11 which represents Q factors and eye diagrams of 2-Channel WDM system without dispersion compensation and with DCF and FBG compensation techniques in two different configurations; 1-stage and 2-stage, It is clearly observed that the system without dispersion compensation has low Q factor for both channels 1 and 2 and an average closed eye diagram. Its performance is enhanced by adding DCF 1-stage compensation technique while its resulting Q factor is larger in the two channels and its eye diagrams are more open. By adding another stage (2-stage configuration) the system keeps on improving and the resulted Q factor and eye diagram in the 2 channels are much more better.

For FBG 1-stage compensation technique the system is not improving in a noticeable way, Q factor and eye diagram in channel 1 and channel 2 are approximately similar to the uncompensated system. While in FBG 2-stage compensation technique, the system get enhanced and shows better Q factor and eye diagram for channel 1 and channel 2. However, the Q factors of FBG technique are very smaller to the ones of DCF techniques and the eye diagrams of FBG techniques are closed comparing to the ones of DCF techniques.

In this section, it is concluded that the DCF stage-1 and stage-2 compensation techniques enhance the system performance and compensate dispersion better than FBG stage-1 and stage-2 compensation techniques.

3.5 Conclusion

In the different sections of this chapter, various parameters effect on the system performance as transmission rate and input power have been studied in addition to the two dispersion compensation techniques FBG and DCF in different designs and for different FBG chirps.

General Conclusion

Dispersion is the main problem in optical fiber communication systems, which has to be mitigated. The development of technology allow many techniques that are performed or still have to be performed to compensate dispersion and enhance the system performance. The most common techniques that already exist are dispersion compensating fiber (DCF), fiber Bragg grating (FBG), electronic dispersion compensation (EDC), optical phase conjugation technique and digital filters.

In this project, FBG and DCF techniques have been applied to WDM systems to minimize the dispersion. Performance analysis have been made during this work to evaluate the role of FBG and DCF in different configurations, and compare between them.

The first simulated system in this project is without dispersion compensation to introduce the effect of distance increasing, transmission rate increasing and input power variations on the optical fiber performance.

FBG with Tanh apodization function, and DCF have been added to 4-Channel WDM system at frequency 1Thz, for 90Km transmission distance, in three configurations; pre-compensation, post-compensation and symmetric compensation DCF and FBG techniques. The Q factors and the eye diagrams of channel 1 have been analyzed and discussed for different bit rates of 3, 6, 9, 12, 15GBit/s and by varying the input power between -10 and 15dBm. Both FBG and DCF; pre-compensation and symmetric compensation techniques; boost the system performance but all of them do not show clear enhancement for higher transmission rates. While, FBG has a feature in compensating nonlinearities in addition to dispersion compensation. FBG and DCF; Post-compensation techniques do not make any enhancement in the system performance.

8-Channel WDM system at frequency 1Thz, and 60Km transmission distance has been analyzed by discussing the performance parameters of its channels 1, 5 and 8 when adding Uniform FBG and DCF techniques (pre-compensation, post-compensation and symmetric compensation) , at 5GBit/s transmission speed and 10dBm input power. For all channels 1,5 and 8, DCF and Uniform FBG post-compensation techniques do not enhance the system. While pre-compensation and symmetric compensation Uniform FBG and DCF techniques make a boost in system performance.

4-Channel WDM system at 1Thz frequency and 120Km transmission distance has been designed and simulated at 6GBit/s transmission rate and 10dBm input power. Then its performance parameters in both channels 1 and 2 have been discussed and analyzed after adding DCF and IDCFBG multistage techniques. 2-stage technique gives better enhancement than 1-stage technique for both FBG and DCF. However, DCF multistage techniques are widely better than IDCFBG multistage techniques for the two channels performance enhancement.

Future work

- FBG and DCF compensation techniques can be added to systems at very high transmission rates above 100GBit/s.
- Dispersion compensation after detection can be analyzed by studying electronic dispersion compensation (EDC) technique.
- Developing the technology for the modulation process.
- Developing motorized dispersion compensation units for optimization of the duration of femtosecond laser pulses and avoid the use of long lines DCF (FemtoControl).

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Appendix

1. Intersymbol Interference (ISI)

ISI occurs when a pulse spreads out in such away that it interferes with adjacent at the sample instant. This is an unwanted phenomenon caused by impairments in the optical fiber lines. An ambiguity occurs in the determination of the binary data; either it is a zero or a one. Figure 1 represent ISI for a NRZ coding format.

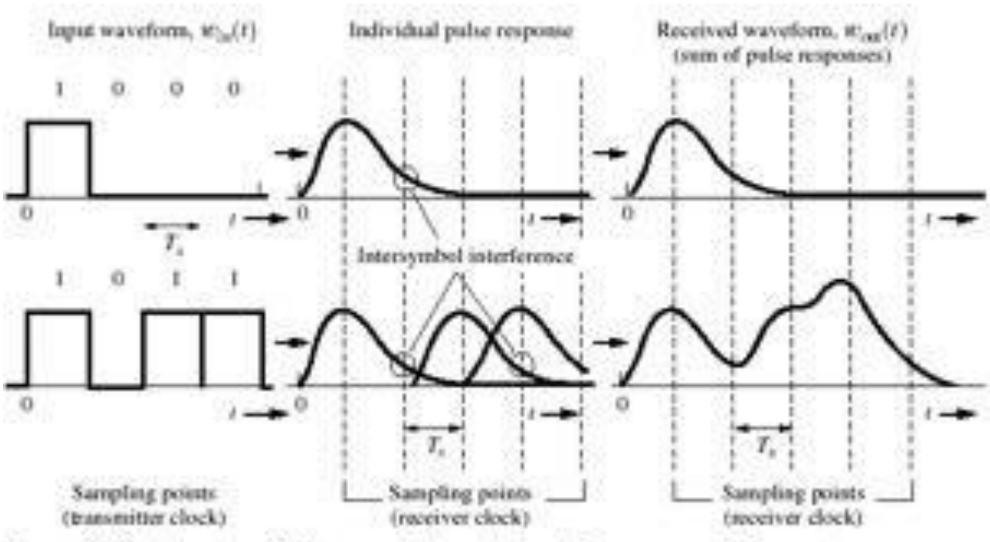

Figure 3–23 Examples of ISI on received pulses in a binary communication system.

Figure 1: Example of ISI on received pulses in a binary communication system

2. 3R regeneration

3R regeneration refers to Re-amplification, Re-shaping and Re-timing the signal. In present optical networks, only the links are optical. Switching and processing in the cross connects is performed in the electrical domain. Based on space switch matrices like the micro electro mechanical switches (MEMS) the signals can be optically bypassed through the nodes and a true all-optical network can be build up. The signals have to pass a variable number of optical nodes and an unknown fiber length on their way to the destination. Signal degradation can arise during fiber transmission as well as in the switching nodes. All-optical 3R signal regeneration is needed to avoid the accumulation of noise, crosstalk and non-linear distortions and to ensure a good signal quality for transmission over any path in the all optical network. 3R regeneration is represented in figre2 and figure3. [16]

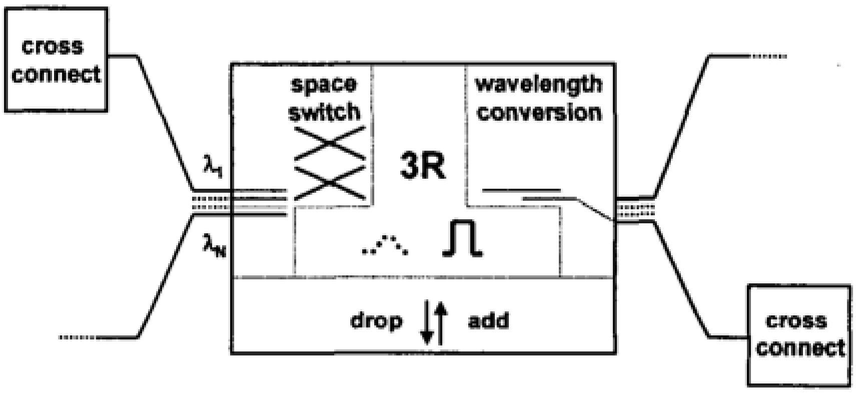

Figure 2: Optical cross connects with 3R regenerators [16]

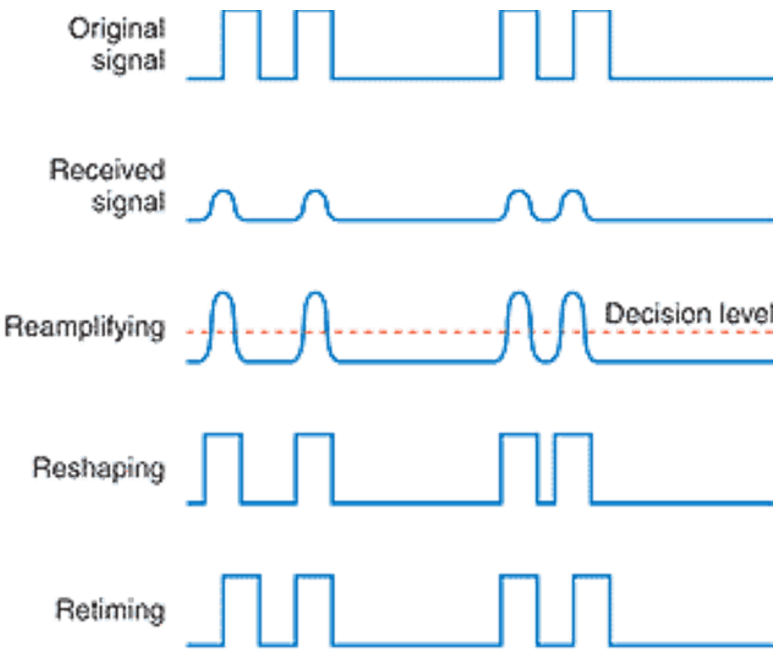

Figure 3: 3R regeneration

3. Eye diagram

The Eye diagram shows the superposition of all mutually overlapping bits in the signal. It takes its name from the fact that it has the appearance of a human eye. It is created simply by superimposing successive waveforms to form a composite image. It is used to look at digital signals for recognizing the effects of distortion. The Eye opening indicates the differentiability of the logic 1 from the logic 0. The more the Eye is wide open, the greater the differentiability is. [17]

Figure 4 illustrates the eye diagram.

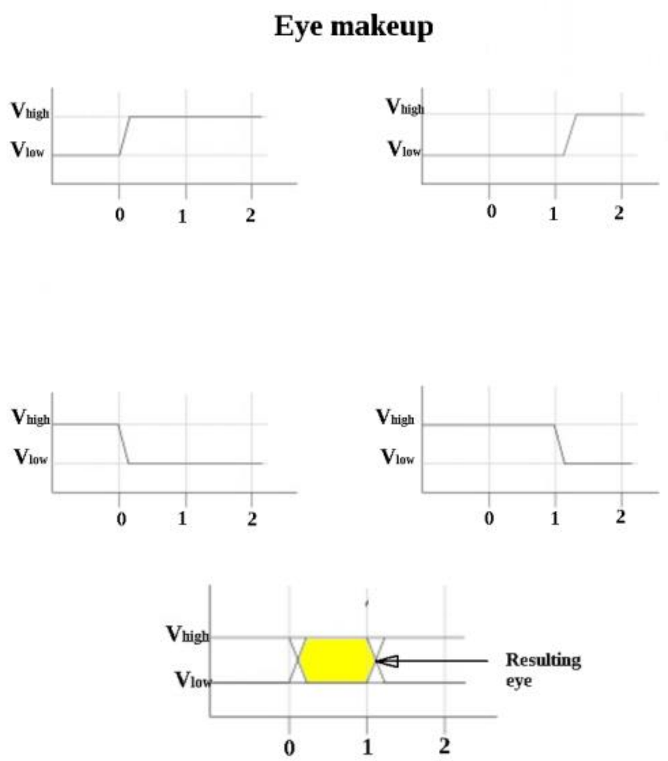

Figure 4: Eye diagram obtained from the superposition of bit sequences 011, 001, 100 and 110