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Title:

Study, Simulation and Estimation of Losses of a DWDM Point-to-Point Topology Network Using OTDR

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Dedication

I dedicate this humble work:

- *To the memory of my father who would have been happy to see me graduating, you've taught me how to truly believe in myself. I've learned, through you, to have faith that with a little luck, and a lot of hard work, I can accomplish absolutely anything and everything.*
- *To my mother, thank you so much for never giving up on me, and pushing me to be my very best. I couldn't have become who I am without your guidance and support.*
- *To my brother "Yacine", the best brother in the world who has been encouraging me in every aspect of the life.*
- *To Miss Cherifi, for her support, advice and constant encouragement. Thank you for being such a good teacher who keeps motivating and pushing us towards our dreams.*
- *To my grandma "Ayi" for her support and love.*
- *To all the family Yahi specially my aunts "Salima and Zahia" as well as my uncle "Ali" who always believed in me and helped me to achieve my goals.*
- *To all the family Chelihi specially my aunt "khdaouedje".*
- *To my project partner "Fatma Zohra" and her family.*
- *To my best friend "Mohammed" for his advice and guidance.*
- *To all my friends without exception.*
- *To everyone who believed in us and helped us to accomplish this project.*

Chelihi Nehad

Dedication

I am dedicating this thesis:

- *To my mother whose love for me knew no bounds, who taught me the value of hard work.*
- *To my small family, who was the source of my aspiration and ambitions.*
- *To my dear "Khalil".*
- *To my project partner, for all the enjoyable time we shared together.*
- *To my grandmother gone forever away from my eyes and who left a void never to be filled in my life. I will make sure your memory lives on as long as I shall live.*

Bouhadda Fatma Zohra

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Abstract

Single mode optical fibers are one of the major transmission media used for long distance communication, due to their very low loss and high bandwidth. The most important properties that affect the system performance are fiber attenuation and dispersion. To improve the overall system performance and reduce dispersion, several compensation technologies are proposed, but the most used ones are: Dispersion Compensation Fiber (DCF) and Fiber Bragg Grating (FBG).

The aim of this project is to study the effect of the input power and the two different compensation techniques DCF and FBG on the performance of an eight channel Dense Wavelength Division Multiplexing (DWDM) line topology designed at wavelength 1550 nm, at three transmission speeds: 30, 60 and 90 Gbps. OptiSystem v.7.0 is used for building the overall system and carrying out simulations. The performance of the system is reported on the basis of eye diagram, Q-factor and Bit Error Rate (BER). The efficiencies of the two compensation methods, at high and low bit rates and input powers, are compared and presented in our final result discussion. In addition, a practical study have been done on the system by measuring the optical losses of the link using an optical time domain reflectometer (OTDR) at both 1310 and 1550 nm wavelengths to ensure its reliability and readiness to function well.

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List of Abbreviations

ADZ	Attenuation Dead Zone
APC	Angled Physical Contact
APD	Avalanche Photodiode
BER	Bit Error Rate
CDM	Code Division Multiplexing
CDMA	Code Division Multi-Access
CRT	Cathode Ray Tube
CW	Continuous Wave
CWDM	Coarse Wavelength Division Multiplexing
DCF	Dispersion Compensation Fiber
DCM	Dispersion Compensation Module
DEMUX	Demultiplexer
DSF	Dispersion Shifted Fiber
DWDM	Dense Wavelength Division Multiplexing
EDC	Electronic Dispersion Compensation
EDFA	Erbium Doped Fiber Amplifier
EDZ	Event Dead Zone
EMS	Externally Modulated Subsystem
FBG	Fiber Bragg Grating
FC	Ferrule Connector
FDM	Frequency Division Multiplexing
FTTH	Fiber-To-The Home
FWHM	Full Width at Half Maximum
FWM	Four-Wave Mixing
IL	Insertion Loss
ITU-T	International Telecommunication Union – Telecommunication Standarzation Section
LAN	Local Area Network
LASER	Light Amplification by Stimulated Emission of Radiation
LC	Lucent Connector
LCD	Liquid Crystal Display
LED	Light Emitting Diode
MMF	Multimode Fiber

List of Abbreviations

MPO	Multi-Fiber Push On
MTP	Multi-fiber Termination Push-on
MUX	Multiplexer
MZM	Mach-Zehnder Modulator
NRZ	Non-Return-to-Zero
NZD	Non-Zero Dispersion
OA	Optical Amplifier
OADM	Optical Add/Drop Multiplexer
OC	Optical Carrier
O-E-O	Optical-Electrical-Optical
OPC	Optical Phase Conjugation
ORL	Optical Return Loss
OSNR	Optical Signal to Noise Ratio
OTDR	Optical Time Domain Reflectometer
PC	Physical Contact
PDH	Plesiochronous Digital Hierarchy
PMD	Polarization Modal Dispersion
PON	Passive Optical Network
PRBS	Pseudo Random Binary Sequence
Q-Factor	Quality Factor
RA	Raman Amplifier
RF	Radio Frequency
ROF	Radio Over Fiber
RZ	Return-to-Zero
SBS	Stimulated Brillouin Scattering
SC	Square Connector
SDH	Synchronous Digital Hierarchy
SFF	Small Form Factor
SMF	Single Mode Fiber
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifier
SONET	Synchronous Optical Network
SPM	Self-Phase Modulation

List of Abbreviations

SRS	Stimulated Raman Scattering
ST	Straight Tip
STM	Synchronous Transport Module
STS	Synchronous Transport Signal
TDM	Time Division Multiplexing
TIR	Total Internal Reflection
UPC	Ultra-Physical Contact
WDM	Wavelength Division Multiplexing
XPM	Cross-Phase Modulation

Introduction

With the rapid progress in information and communication technologies due to the Internet, electronic commerce, computer networks, multimedia, voice, data, and video, the need for a transmission medium with the bandwidth capabilities for handling such vast amounts of information is paramount. Fiber optics, with its comparatively infinite bandwidth, has proven to be the solution.

The increasing interest in signal transmission through optical fibers has led into the use of DWDM which is an optical multiplexing technology used to increase bandwidth over existing fiber networks. DWDM works by combining and transmitting multiple signals simultaneously at different wavelengths on the same fiber. The technology creates multiple virtual fibers, thus multiplying the capacity of the physical medium. However, dispersion and nonlinearities are the main limiting factors for the high-speed optical DWDM network. Therefore, some amplification and dispersion compensation scheme must be used to achieve the tremendous benefits of the DWDM system and improve the performance of the network.

This report contains four main chapters that are organized as follows:

Chapter 1: Introduces the basics of optical communications, the components that make up an optical fiber system and their operations. It describes also the structure of an optical cable, its types and characteristics.

Chapter 2: Introduces DWMD systems, and shows their importance in transmitting multiple information streams over the fiber. Besides, it provides an overview of the different components needed to build such networks.

Chapter 3: Devoted to the design and simulation of a real case DWDM line transmission system of an 8 channel operating at different bit rates using Optisystem v.7.0 software.

Chapter 4: Deals with the loss measurements of the DWDM system described in chapter three at two different wavelengths using OTDR.

Conclusion: Summarizes the outcome of this work and gives some suggestions for the future work.

1.1 Introduction

Since telecommunications need always to transmit more data faster, considerable improvements have been made in optical fiber technology; enabling networks to provide high capacity with huge bandwidth, where speed is a major requirement.

1.2 General overview of optical fiber communication system

Conceptually, an optical fiber communication system is similar to any type of communication system. It conveys the data from the information source over the transmission medium to the destination by changing electrical signals into light [1].

Basically an optical fiber communication system comprises three main components as represented in figure 1.1:

- Optical transmitter
- Optical cable
- Optical receiver

There are also some additional elements that are important in this communication system like: connectors, switches, couplers, multiplexing devices, amplifiers and splices.

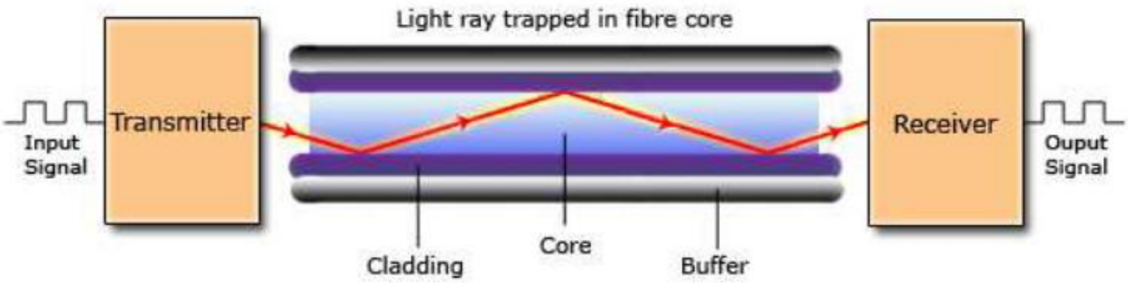


Figure 1.1 Basic optical fiber communication system [19].

1.2.1 Optical transmitter

The role of an optical transmitter is to transform the electrical signal into optical form and then launch the resulting optical signal into the optical fiber. It consists of four components which are:

- **Driver or data source:** it produces a pseudo random binary sequence (PRBS) which represents the information to be transmitted.
- **Non-return-to-zero (NRZ) pulse generator:** it transforms the binary data into electrical pulses.

- **Light source:** it can be a Light Emitting Diode (LED), or a Light Amplification by Stimulated Emission of Radiation (LASER).
- **Mach-Zehnder Modulator (MZM):** it is an external modulator used to vary the intensity of the light coming from the light source with respect to the output of NRZ pulse generator.

Further details about the function of each of the previous components are given in Appendix A. The figure 1.2 represents the optical transmitter block diagram that includes all the above components.

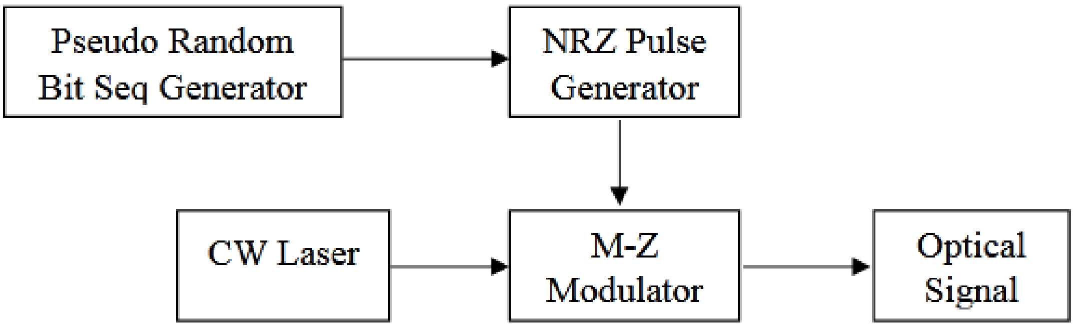


Figure 1.2 Optical transmitter block diagram [9].

1.2.2 Optical cable

An optical fiber is a flexible, thin, transparent strand of very pure glass where the information is transmitted as light pulses. It is composed of three main layers as shown in figure 1.3:

- **Core:** it is the light transmission element at the center of the optical fiber, typically made of glass or silica. The diameter of the core depends on the used applications, but the larger the diameter, the more light can travel through the optical fiber.
- **Cladding:** it surrounds the core and is made of material with a slightly lower refraction index than that of the core. This difference in the indices causes light to propagate under the total internal reflection (TIR) at the core-cladding interface.
- **Coating:** it is the outer layer of the optical fiber; it serves as a "shock absorber" to protect the core and cladding from any physical damage. The coating usually comprises one or more layers of a plastic material to protect the fiber.

For further protection, the optical fiber is covered with a buffer to protect it from damage and a jacket bundled with other fibers to make up a larger cable [20].

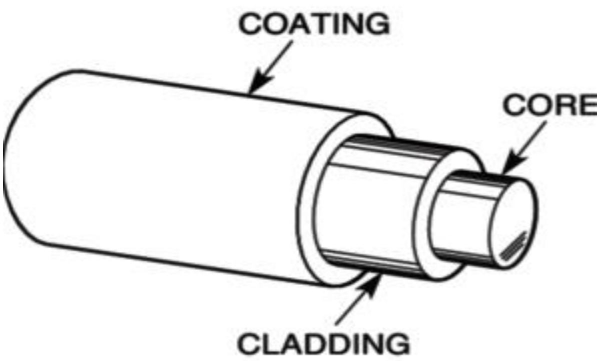


Figure 1.3 Optical fiber structure [21].

1.2.2.1 Transmission principle

When light passes through the core which has a refractive index n_1 greater than the refractive index of the cladding n_2, it will bend or refract away from an imaginary line perpendicular to the surface (normal line). As the angle of the beam through the core gets greater with respect to the normal line, the refracted light through the cladding bends further away from the perpendicular line.

At one particular angle called the critical angle $\emptyset_c$ given by:

$$sin\emptyset_c = \frac{n_2}{n_1} \tag{1-1}$$

the refracted light will no more propagate in the cladding, instead it will travel along the core-cladding interface.

If the angle of the beam travelling along the core is greater than this critical angle, the refracted beam will be reflected entirely back into the core, this is known as "total internal reflection" which is the responsible phenomenon for guiding light along the optical fiber [22].

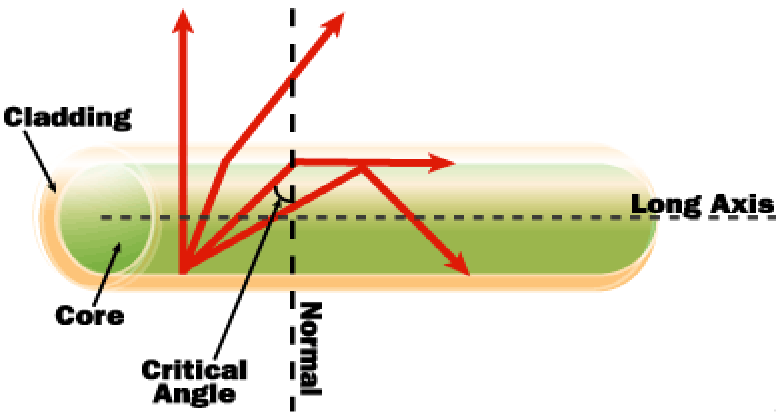


Figure 1.4 Principle of total internal reflection [22].

1.2.2.2 Fiber types

There are two main categories of optical fibers that are used today; single mode fibers and multimode fibers that are represented in figure 1.5.

a. Single mode fiber

Single mode fiber (SMF) has extremely small core diameter that allows only one mode of light to propagate through it in a straight line. Hence, the attenuation is reduced enabling the signal to travel over long distances.

b. Multimode fiber

Multimode fiber (MMF) has a larger core diameter than the single mode fiber that allows multiple light modes to propagate through it. This will increase the number of reflections at the core-cladding interface. Hence, the attenuation and losses increase which then cause the quality of the signal to deteriorate over long distances. Therefore, it is better to use it for short distances.

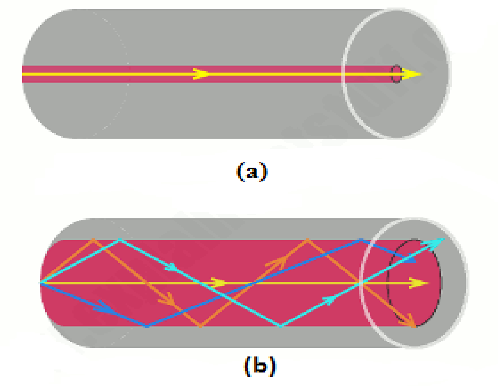


Figure 1.5 The two basic types of optical fibers

(a) Single mode fiber (b) Multimode fiber [23].

1.2.2.3 Fiber losses

Fiber losses represent the performance limiting factors of optical communication systems that reduce the minimum amount of power required by optical receivers for accurate signal recovery.

a. Attenuation

Attenuation, also known as the transmission loss, is the rate at which the light signal intensity decreases with respect to the distance travelled through the transmission medium [2].

Mathematically, the attenuation is defined as the ratio of the optical power output to the optical power input in the fiber. The attenuation coefficient α is wavelength dependent and directly proportional to the length of the cable. The loss in dB per kilometer of fiber is represented by equation (1.2)

$$\alpha(dB/Km) = -\frac{10}{L} Log_{10}\left(\frac{P_{out}}{P_{in}}\right) \tag{1-2}$$

Where L, P_{in}, and P_{out} are the total length of the optical fiber, the input power and the output power respectively.

There exist three types of phenomena that cause the attenuation in a fiber: absorption, scattering, and imperfection losses of the optical energy.

1. **Absorption loss**

It is related to the material composition and the fiber fabrication process. It results in the dissipation of some of the transmitted optical power as heat in the fiber. Light absorption may be either intrinsic or extrinsic.

❖ **Intrinsic loss**

It is caused by the interaction of the propagating light signal with one or more major components of glass constituting the fiber. An example of such interaction is the infrared absorption band of pure silicate glass SiO_2 that is shown in figure 1.6. However, in the wavelength range of interest in optical communication (from 0.8 to 1.7 μm), intrinsic absorption has a negligible effect.

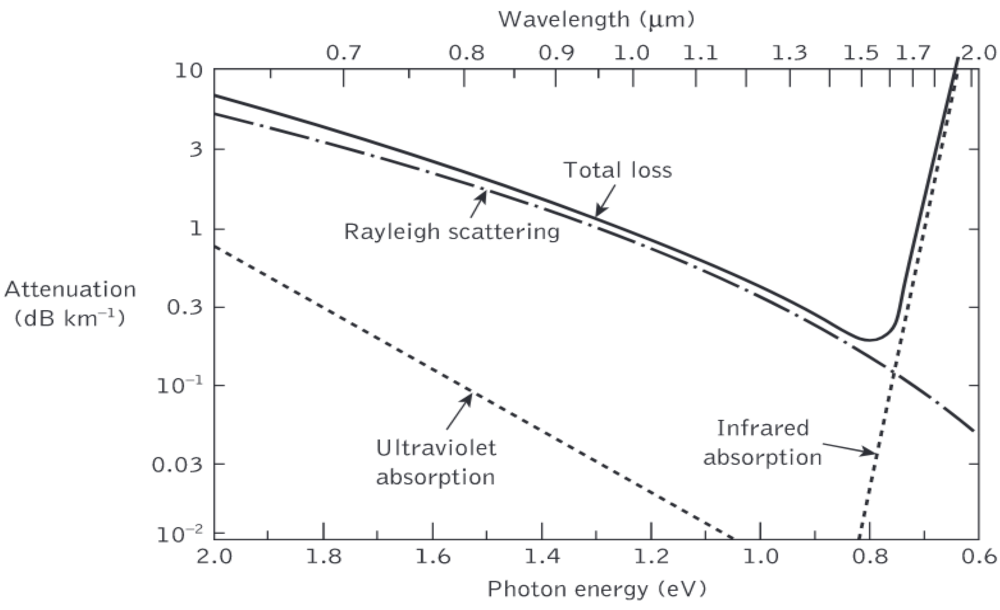


Figure 1.6 The attenuation spectra for the intrinsic loss mechanism in pure Silicate glass[1].

❖ **Extrinsic loss**

It is much more significant and it results from the presence of metallic ion impurities in glass such as: Fe^{+2},Cu^{+2}, C^{+2}, Ni^{+2}, Mn^{+3} and Cr^{+3}.

The contamination of these elements can be reduced to acceptable levels by glass refining techniques. However, the main source of extrinsic absorption in silica fibers is the presence of hydroxyl (OH^{-}) dissolved in glass. These hydroxyl groups have fundamental vibrations that give rise to overtones appearing harmonically at 1.38, 0.95 and 0.72 μm, as illustrated in figure 1.7.

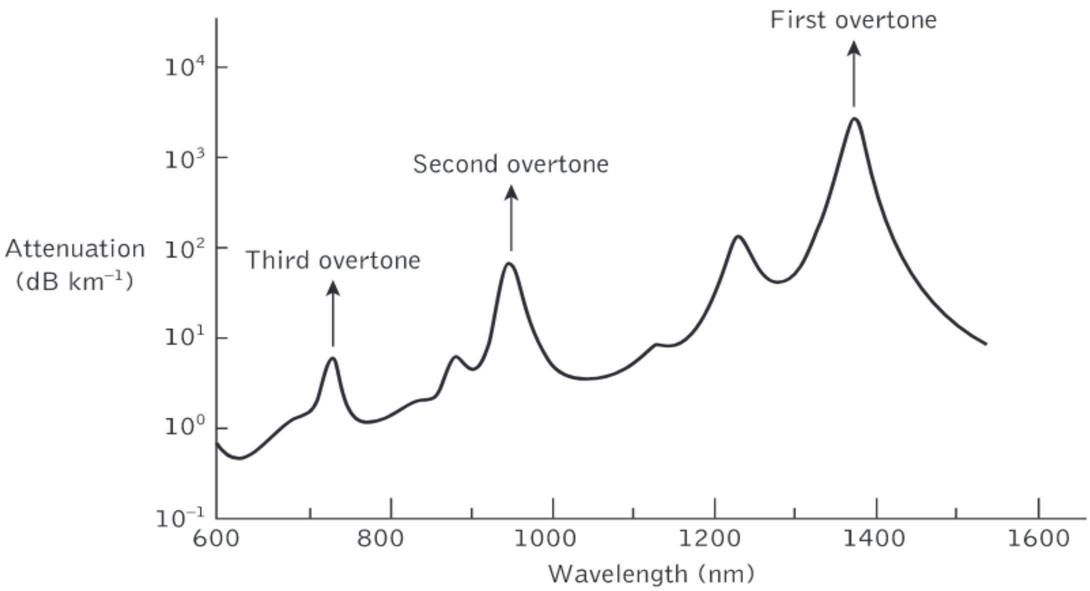


Figure 1.7 The absorption spectrum for the hydroxyl (OH) group in Silica [1].

2. **Scattering loss**

It is caused by the interaction of light with density fluctuations within a fiber. The change in density occurs during manufacturing the optical fiber; where regions of higher and lower molecular density areas relative to the average density of the fiber are created. Then when light passes, it will be scattered in all directions [24]. We distinguish two main types of scattering loss:

❖ **Linear scattering:** which causes the transfer of some or all of the optical power contained within one propagating mode to another different mode keeping frequency unaltered [1].

❖ **Non linear scattering:** where the optical power is transferred in either forward or backward direction to the same, or other modes at a different frequency. It is classified into two classes: Stimulated Raman Scattering (SRS) and Stimulated

Brillouin Scattering (SBS) that will be discussed later on in the non linear effects section [1].

The linear scattering can be further categorized into two types:

- **Rayleigh scattering**

It is caused by inhomogeneities of random particles that have a radius less than approximately 1/10 the wavelength of the radiation. These inhomogeneities manifest themselves as refractive index fluctuations. The scattered light carries the same energy as the incident light (elastic scattering) and it is angle independent. For a single component glass, the Rayleigh loss is given by:

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F \tag{1-3}$$

Where γ_R is the Rayleigh scattering, λ is the optical wavelength, n is the refractive index of the medium, p is the average photo elastic coefficient, β_c is the isothermal compressibility at a fictive temperature T_F and K is the Boltzmann's constant [1].

- **Mie scattering**

It may occur at inhomogeneities which are comparable in size (> λ /10) to the guided wavelength. This results from the non-perfect cylindrical structure of the waveguide. The scattered light is unequal in energy to the incident light (inelastic scattering) and it is angle dependent where the energy is most intense towards the direction of the incident light [1].

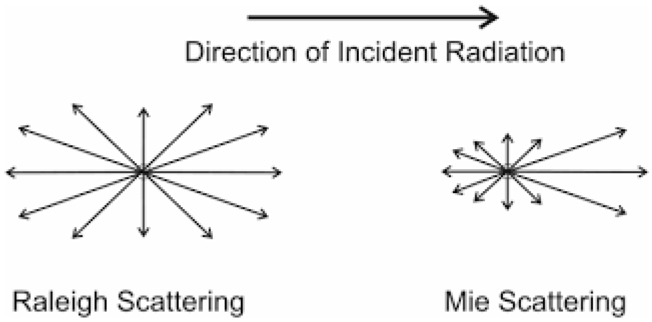


Figure 1.8 Difference between Rayleigh and Mie scattering [25].

3. **Imperfection loss**

Imperfection loss includes: bending and splicing losses.

❖ **Bending loss**

It is a phenomenon that occurs when the optical fiber is bent tightly above the critical bend radius. Reasons for these bend losses are poor cable design, microscopic fiber deformation and improper handling of the optical fiber [10].

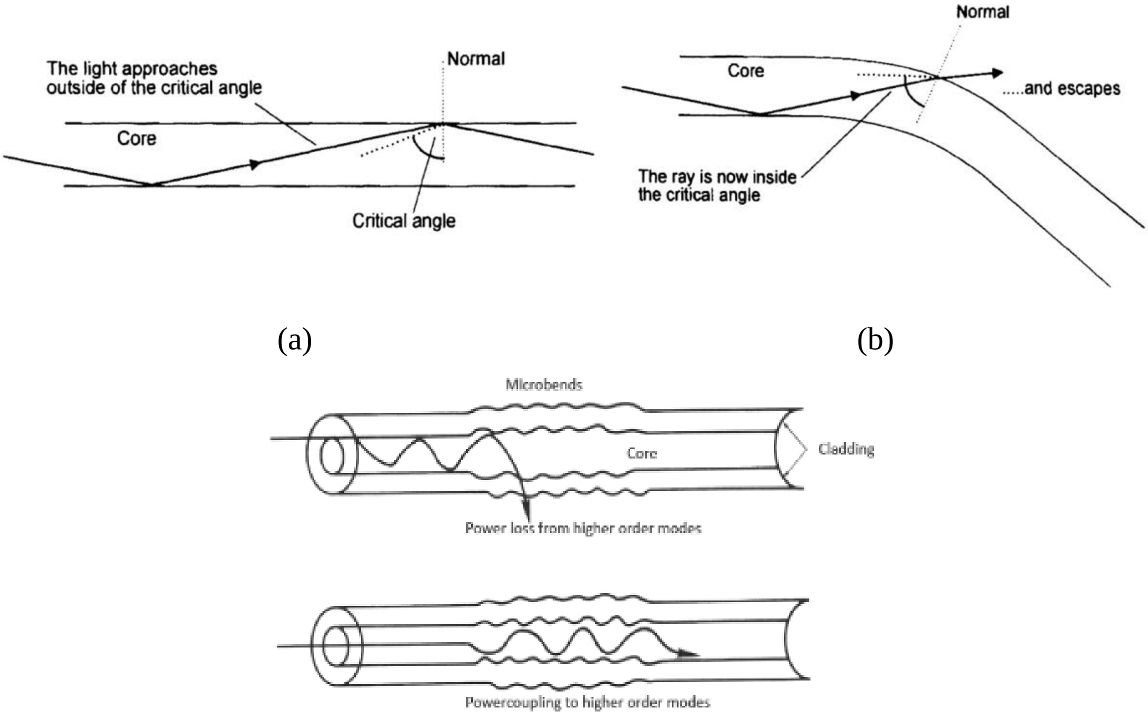
Fibers can be subjected to two types of bends:

- **Macro Bending**

  It occurs when the fiber is sharply bent so that the light travelling down the fiber is refracted out of the core into the cladding region.

- **Micro Bending**

  It is associated with repetitive micro scale fluctuations in the fiber radius due to non uniformity in the fiber diameter during the fabrication process or in response to radial pressures. The result is coupling of energy between guided and non-guided wave modes in the fiber.



(a) (b)

(c)

Figure 1.9 Comparison between Macro and Micro bendings in an optical fiber

(a) The usual situation (b) Macro bending (c) Micro bending [5].

❖ **Splicing loss**

Splicing loss refers to the part of the optical power that is not transmitted through the junction of two connected fibers and is radiated out of the fiber. The total loss in decibels at the fusion splice is given by the following equation:

$$\alpha_{Splice} = 10log_{10}\frac{P_{in}}{P_{trans}} \quad (1\text{-}4)$$

Where P_{in} is the total power incident on the fusion splice and P_{trans} is the portion of the optical power transmitted across the fusion splice. Since $P_{in}>P_{trans}$, the splice loss is always a positive number [26].

The loss is caused by some extrinsic or intrinsic reasons. Extrinsic reasons include the defective splicing due to core-to-core offset, tilt (misalignment) or deformation at the splice. Intrinsic reasons are the differences in the optical characteristics of the fibers, in particular, core diameter, and numerical aperture.

b. Dispersion

It is the process which cause the signal carried in an optical fiber to degradate. This degradation occurs because of the different components of radiation having different frequencies and propagating with different velocities. Hence, they do not arrive simultaneously at the end, and eventually the information will be lost.

The types of dispersion that affect the optical fiber are: modal dispersion, material dispersion, waveguide dispersion, chromatic dispersion and polarization-mode dispersion [11].

1. Modal Dispersion

It results from light taking different paths, or modes as it passes through the fiber. The number of modes the light can take is determined by the diameter of the fiber core, the refractive indices of the fiber core and cladding and the wavelength of the light. Depending on the mode, some parts of the light will pass through the fiber more quickly than others. The difference in travel time can cause parts of the light pulses to overlap each other, or in extreme cases to arrive in a different order from the order they were transmitted. The signal is then no longer usable.

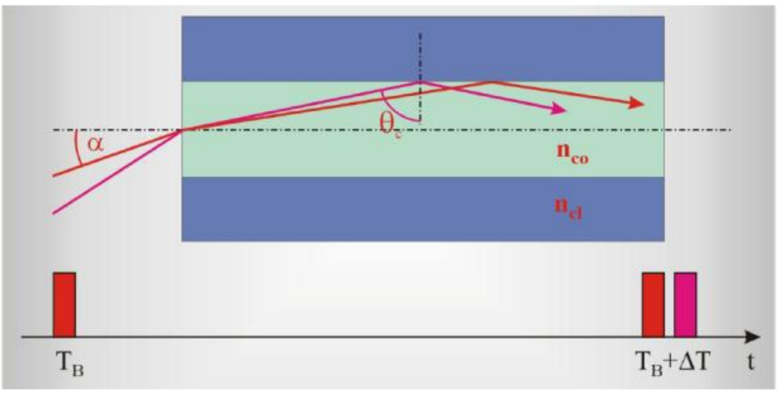


Figure 1.10 Modal dispersion in multimode fiber [11]

2. Material Dispersion

It is the result of different wavelengths of light traveling at different velocities in the fiber. The slower wavelengths begin to lag behind as the light travels down the fiber core, causing the light to spread. If the light must travel a great distance, the lag in the slower wavelengths can cause them to overlap the faster wavelengths of the bits following them. These overlaps can degrade and ultimately destroy the signal.

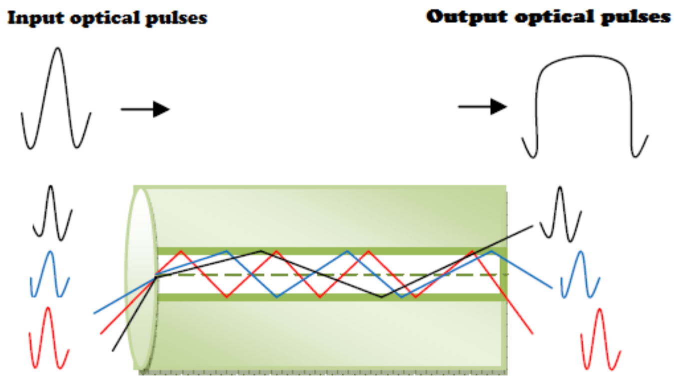


Figure 1.11 Effects of material dispersion

3. Waveguide Dispersion

It occurs in single mode fiber as the light passes through not only the core, but also part of the cladding. Because, the core has a higher refractive index than the cladding, the light will be traveling more slowly through the core than through the cladding.

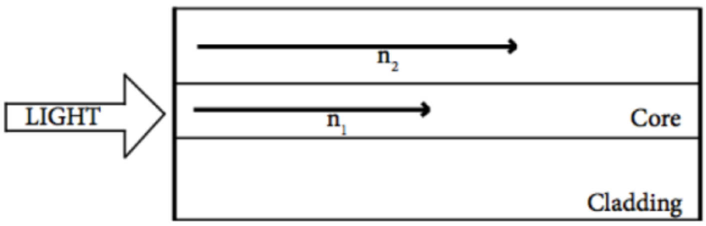


Figure 1.12 Effect of waveguide dispersion [27].

4. Chromatic Dispersion

It refers to the different spectral components of light pulse traveling at different velocities with a propagation delay, this delay results from the combination of effects of material dispersion and waveguide dispersion.

5. **Polarization modal dispersion**

Polarization modal dispersion (PMD) is a dispersion phenomenon usually associated with single mode fibers, where two polarized modes travel at different speed due to the variation in the cylindrical geometry of the fiber that results from the mechanical stress exerted upon it as well as the imperfections during the manufacturing process.

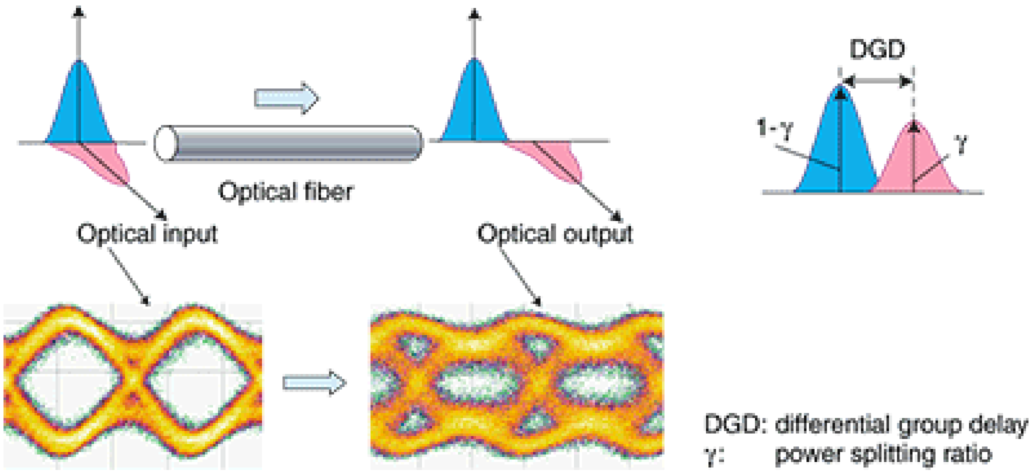


Figure 1.13 Polarization mode dispersion in single mode fibers [28].

c. **Non linear effects**

There exist two categories of non linear effects. The first arises due to the inelastic scattering where the light waves interact with phonons (molecular vibrations) in the silica medium. The second set of nonlinear effects is due to the dependence of the refractive index on the intensity of the applied electric field [3].

1. **First category**

This category includes the two effects of Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS). Both of them can be understood as scattering of a photon to a lower energy photon such that the energy difference appears in the form of a phonon. The main difference between the two is that optical phonons participate in Raman scattering, whereas acoustic phonons participate in Brillouin scattering. Both scattering processes result in a loss of power at the incident frequency.

Even though SRS and SBS are quite similar in their origin, different dispersion relations for acoustic and optical phonons lead to the following differences: SBS occurs only in the backward direction whereas SRS can occur in both directions, the scattered light is shifted in frequency by about 10 GHz for SBS but by 13 THz for SRS, the Brillouin gain spectrum is extremely narrow compared to the Raman gain spectrum [2].

2. **Second category**

The most important nonlinear effects in this category are Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Four-Wave Mixing (FWM).

❖ **Self-Phase Modulation (SPM)**

SPM is due to the dependence of the refractive index on the intensity of light propagating in the fiber. This dependence causes an induced phase shift which is proportional to the intensity of the pulse. Hence, different parts of the pulse undergo different phase shifts, which gives rise to chirping of the pulses which in turn enhances the pulse broadening effects of chromatic dispersion. So, the chirping effect is proportional to the transmitted signal power [4].

❖ **Cross-Phase Modulation (XPM)**

The intensity dependence of the refractive index can also lead to another nonlinear phenomenon known as Cross-phase Modulation (XPM). It occurs when two or more optical channels are transmitted simultaneously inside an optical fiber using the Wavelength Division Multiplexing (WDM) technique. In such systems, the nonlinear phase shift for a specific channel does not depend only on the power of that channel but also on the power of other channels. Hence, the strength of XPM increases with the number of channels and also it becomes stronger as the channel spacing is made smaller [2].

❖ **Four-Wave Mixing (FWM)**

In a WDM system, the intensity dependence of the refractive index does not only induce phase shifts within a channel but also gives rise to signals at new frequencies.

If three optical fields with carrier frequencies ω_1, ω_2 and ω_3 interact inside the fiber simultaneously, they generate a fourth field whose frequency ω_4 is related to the other frequencies by a relation $\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3$. This phenomenon is called four-wave mixing. FWM does not depend on the bit rate but it is critically dependent on the channel spacing and fiber chromatic dispersion; where decreasing the channel spacing increases the four-wave mixing effect, and so does decreasing the chromatic dispersion [2]. Figure 1.14 Represents the FWM.

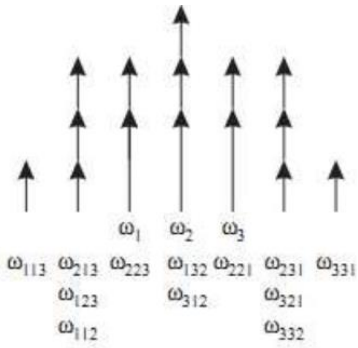


Figure 1.14 Four wavelength mixing [3].

1.2.2.4 Fiber advantages and disadvantages

a. Advantages

- Greater bandwidth and faster speed.
- Thinner and light-weighted.
- Higher carrying capacity.
- Less signal degradation (typically less than 0.3 dB/km).
- Difficult to place a tap or listening device on the line, providing better physical network security.
- Long Life span (usually have a longer life cycle for over 100 years).
- High electrical resistance, so safe to use near high-voltage equipment.

b. Disadvantages

- Fiber optic cable can only be used on the ground, and it cannot work with mobile communication.
- Limited physical arc of cables, hence more susceptible to damage during installation and construction activities.
- High installation costs.
- Repeaters are needed during the transmission to boost the signal.

1.2.3 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. It must achieve this function while satisfying certain system requirements such as desired level of signal-to-noise ratio (SNR) and bit error rate (BER). The main component of an optical receiver is a photodetector, which converts the optical power into electrical current.

To achieve the best performance, a photodetector needs to meet a set of requirements like: the good responsivity (sensitivity) to a wide range of wavelengths used for transmission, low noise characteristics and the zero sensitivity to temperature variations. Even though there are several types of photodetectors, the semiconductor-based photodetectors (photodiodes) are used exclusively for optical communication [6]. The most common photodiodes used in optical systems are PIN photodiode and Avalanche Photodiode (APD) that are discussed in Appendix A.

After converting the optical signal into electrical one using a photodiode, a low noise amplifier is used in order to boost the electrical signal to a suitable level for additional signal processing. Then, a signal conditioning circuitry is added depending on the modulation type and the electrical output requirements. Figure 1.15 shows an optical receiver block diagram.

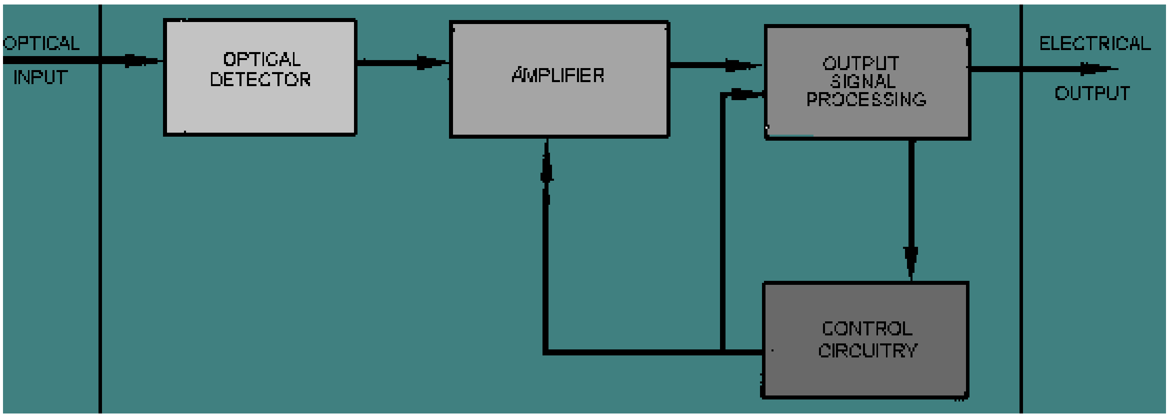


Figure 1.15 Optical receiver block diagram [29].

1.3 Conclusion

Optical fiber has become the preferred medium for the transmission of voice, video and data, because it offers a greater bandwidth and it is less bulky than copper cables. However, with the challenge of increasing capacity and reliability while constraining cost, deploying new technologies such as Synchronous Optical Network /Synchronous Digital Hierarchy (SONET/SDH) and Wavelength Division Multiplexing (WDM) has become a necessity.

2.1 Introduction

With the exponential growth in communication, caused mainly by the wide acceptance of the Internet, many carriers are finding that their estimates of fiber needs have been highly underestimated. Although most cables included many spare fibers when installed, this growth has used many of them and new capacity is needed. As a solution for this, a new technology was developed known as Dense Wavelength Division Multiplexing (DWDM) which allows enormous amounts of data carried on distinct wavelengths to traverse a single network link.

2.2 Evolution of optical transport technologies

The migration from PDH to SONET/SDH took roughly 10 years for the transport network industry. As this technology swap comes to an end, WDM technology revolutionizes the network industry, with the possibility of transport bit rates above 10 Gb/s as well as transparency to signal encodings. The basics of these technologies and the main differences between them are discussed further.

2.2.1 Plesiochronous Digital Hierarchy (PDH)

The Plesiochronous Digital Hierarchy is a telecommunication network transmission technology that is designed to transport huge amounts of data over large scale digital networks.

Each stream of data is running at a clock rate which is very close but not exactly in time with one another, hence the name *Plesiochronous* was given which means “nearly synchronous”. With multiplexed signals arriving at different end times, there has to be a mechanism for reconstituting the various streams into the original signal form. Thus, PDH allows signals to be bit stuffed until they are all the same length, so that they can be successfully demultiplexed and the stuffed bits are then discarded [30].

PDH supports a data transmission rate of 2.048 Mbps. This rate breaks into different 30 channels of 64 Kbps along with two different 64 Kbps that are used to perform the tasks of synchronization and signaling [31]. The rates E2, E3, E4 and E5 derived respectively from 2.048 Mbps that corresponds to E1 are shown in figure 2.1.

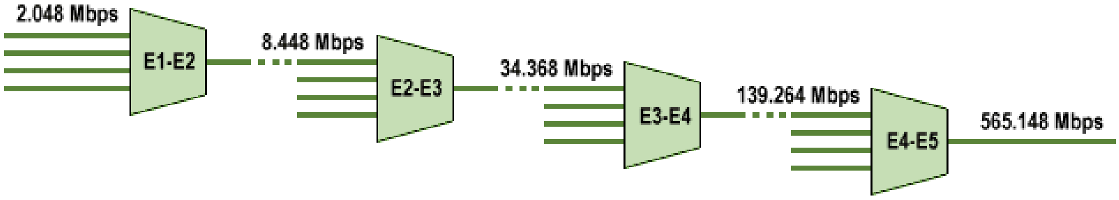


Figure 2.1 PDH level hierarchy diagram [31].

2.2.2 Synchronous Digital Hierarchy and Synchronous Optical Network

As PDH was not scalable to support high capacity bandwidth and hence was not suitable to accommodate growing traffic need. SDH was developed as the European Standard for transmission and multiplexing for high speed signals while SONET as the American one.

The information transmitted by SONET/SDH is organized into frames. These frames are transmitted continuously one after another. Each frame consists of a collection of overhead fields and a payload. SONET/SDH equipment constructs these frames in the electrical domain and then transmits them out optically. At the receiving end, the SONET/SDH equipment converts the optical signal into electrical one to process the frames.

The electrical side of the SONET signal is known as the synchronous transport signal (STS). The Synchronous Transport Signal Level -1 (STS-1) has a bit rate of 51.84 Mbps. Lower-rate payloads are mapped into STS-1s, and higher-rate signals are obtained by multiplexing N frames of STS-1s to form an STS-N, where N = 1, 3, 12, 24, 48, 192. The transmission rate of STS-N is N * 51.84 Mbps.

The electrical side of SDH is known as the Synchronous Transport Module (STM), STM-1 has a bit rate of 155.52 Mb/s. The lower-rate payloads are mapped into an STM-1, and higher-rate signals are obtained by multiplexing N STM-1 signals to form an STM-N signal, where N = 1, 4, 16, 64.

The optical side of a SONET/SDH signal is known as the Optical Carrier (OC). The speed of the optical carrier-classified lines labeled as OC-N is N * 51.84 Mbps [7]. The different bit rates associated for the SONET/SDH levels are shown in table 2.1.

Table 2.1 SONET/SDH levels bit rate [7].

SONET signal (Electrical)	Equivalent SDH signal (Electrical)	Optical level	Bit rates (Mbps)
STS-1	_	OC-1	51.84
STS-3	STM-1	OC-3	155.52
STS-12	STM-4	OC-12	622.08
STS-48	STM-16	OC-48	2488.32
STS-192	STM-64	OC-192	9953.28
STS-768	STM-256	OC-768	39813.12

2.2.3 Wavelength Division Multiplexing (WDM)

In fiber optic communications, Wavelength Division Multiplexing (WDM) is a technology where a fiber is used to carry many separate and independent optical channels as shown in figure 2.2. The number of multiplexed channels is increased by reducing the channel spacing. The reduction in channel spacing increases the crosstalk and hence the performance of the system degrades considerably. WDM is an efficient mean for enabling bi-directional communication and increasing the transport capacity, or usable bandwidth particularly for optical single mode fibers [12].

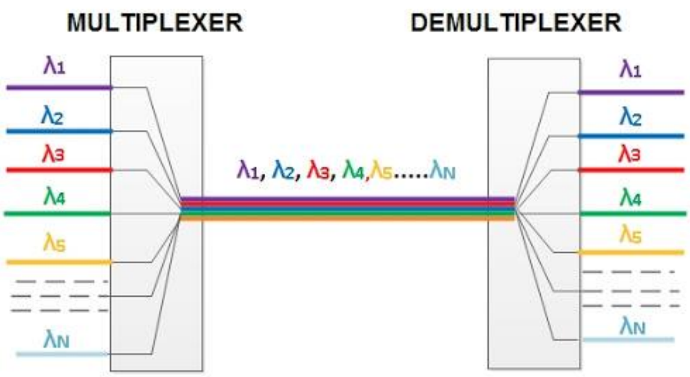


Figure 2.2 Wavelength Division Multiplexing (WDM).

Channel spacing serves as a basis for dividing WDM systems into two different wavelength patterns: Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM).

Typically, CWDM supports up to 18 channels within the range of 1480 nm up to 1620 nm spaced by 20 nm. Whereas, DWDM common spacing may be 200,100, 50, or 25 GHz with channel count reaching up to 128 or more channels at distances of several thousand kilometers with amplification and regeneration along such a route [32]. Table 2.2 illustrates more differences between them.

Table 2.2 Comparison between CWDM and DWDM.

	Channel spacing	**Band used**	**Cost per channel**	**Number of Channels delivered**	**Best Application**
CWDM	Large, 1.6nm -25nm	S (1480 – 1520nm) C (1521– 1560nm) L (1561 – 1620nm)	Low	17 – 18 most	Short haul, Metro
DWDM	Small, 1.6nm or less	C (1521– 1560nm) L (1561 – 1620nm)	High	Hundreds of channels possible	Long Haul

2.3 Networking with DWDM

The demand for Internet bandwidth grows as new applications, new technologies and increased reliance on the Internet continue to rise. Dense wavelength division multiplexing (DWDM) is one technology that allows networks to gain significant amounts of bandwidth to handle this growing need. DWDM is reserved for very close frequency spacing signals, typically less than100 GHz corresponding to 0.8 nm at wavelengths near 1500 nm.

2.3.1 DWDM system components

- Optical transmitters/receivers.
- DWDM mux/demux filters.
- Optical add/drop multiplexers (OADMs).
- Optical amplifiers.
- Transponders (wavelength converters).

2.3.1.1 Optical transmitters/receivers

Transmitters are described as DWDM components because they provide the light source signals which are then multiplexed. The characteristics of optical transmitters used in DWDM systems are highly important to system design. Several individual lasers are typically used to create the individual channels of a DWDM system. Each laser operates at a slightly different wavelength to avoid crosstalk phenomena. Whereas, receivers are used to detect the incoming optical power and extract from it the signal that is being transmitted. They must achieve this function while satisfying certain system requirements such as desired level of signal to noise ratio and bit error rate [13].

2.3.1.2 DWDM mux/demux

The DWDM multiplexer (mux) combines multiple wavelengths created by multiple transmitters and operating on different fibers into a single composite signal. At the receiving end, the demultiplexer (demux) separates all of the individual wavelengths of the composite signal out to individual fibers. The individual fibers pass then the demultiplexed wavelengths to optical receivers.

Generally, Mux and Demux components are contained in a single enclosure. Optical Mux/Demux devices can be passive. Components signals are multiplexed optically, not electronically; therefore no external power source is required.

Figure 2.3 shows N light pulses of N different wavelengths carried by N different fibers combined by a DWDM multiplexer. The N signals are multiplexed into a pair of optical fibers, one for transmit and the other for receive. A DWDM demultiplexer receives the composite signal and separates each of the N component signals and passes each to a fiber. The transmit and receive signal arrows represent client-side equipment [13].

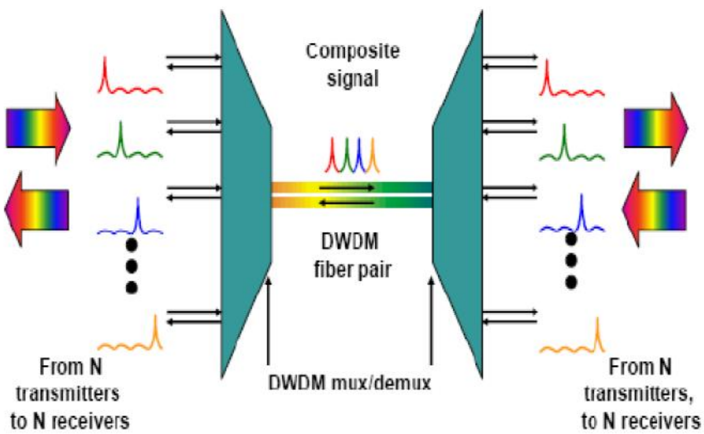


Figure 2.3 Bidirectional DWDM operation [13].

2.3.1.3 Optical add/drop multiplexers (OADMs)

The OADM performs the drop or insert of one or more wavelengths at some point along the transmission span. Rather than combining or separating all wavelengths, the OADM can drop some while passing other ones.

The block diagram below demonstrates the operation of a one channel OADM. This OADM is designed to only add or drop optical signals with a particular wavelength (represented by the red light pulse above). From left to right, an incoming composite signal is broken into two components, drop and pass-through. The OADM drops only the red optical signal stream which is passed then to the receiver of a client device. The remaining optical signals that pass through the OADM are multiplexed with a new add signal stream, which operates at the same wavelength as the dropped signal to form a new composite signal [13].

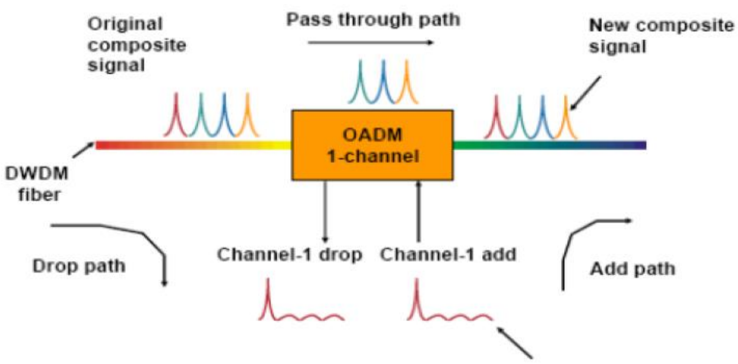


Figure 2.4 One channel OADM operation [13].

2.3.1.4 Optical amplifiers

Optical amplifiers (OAs) boost the amplitude or add gain to optical signals passing on a fiber by directly stimulating the photons of the signal with extra energy. OAs amplify optical signals across a broad range of wavelengths which is very important for DWDM system application [13]. The major types of optical amplifiers include EDFA, RA, and SOA which are discussed further in appendix B.

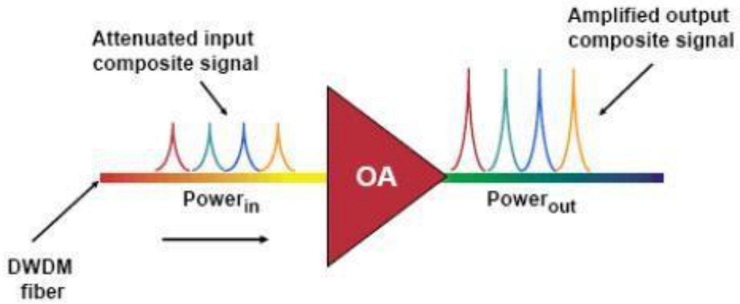


Figure 2.5 Optical amplifier operation [13].

2.3.1.5 Transponders

Transponders convert optical signals from one incoming wavelength to another outgoing wavelength suitable for DWDM applications. They are considered as optical-electrical-optical (O-E-O) wavelength converters. Within a DWDM system the transponder converts the client input optical signal into the electrical domain and then performs either 2R (re-time and re-transmit) or 3R (re-time, re-transmit and re-shape) functions using a 1550 nm band laser [13].

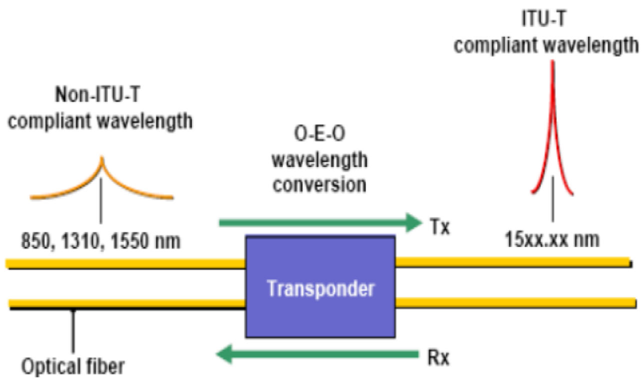


Figure 2.6 Bidirectional transponder operation [13].

The diagram of figure 2.6 shows a transponder which is located between a client device and a DWDM system. From left to right, the transponder receives an optical bit stream operating at one particular wavelength and then converts it to an ITU-compliant wavelength signal which is transmitted to a DWDM system. On the receive side (right to left), the process is reversed. The transponder receives an ITU-compliant bit stream and converts the signals back to the wavelength used by the client device.

2.3.2 Working principle of a DWDM system

Figure 2.7 represents a DWDM system in its most basic representation and the mentioned steps below it describe the principles of its operation:

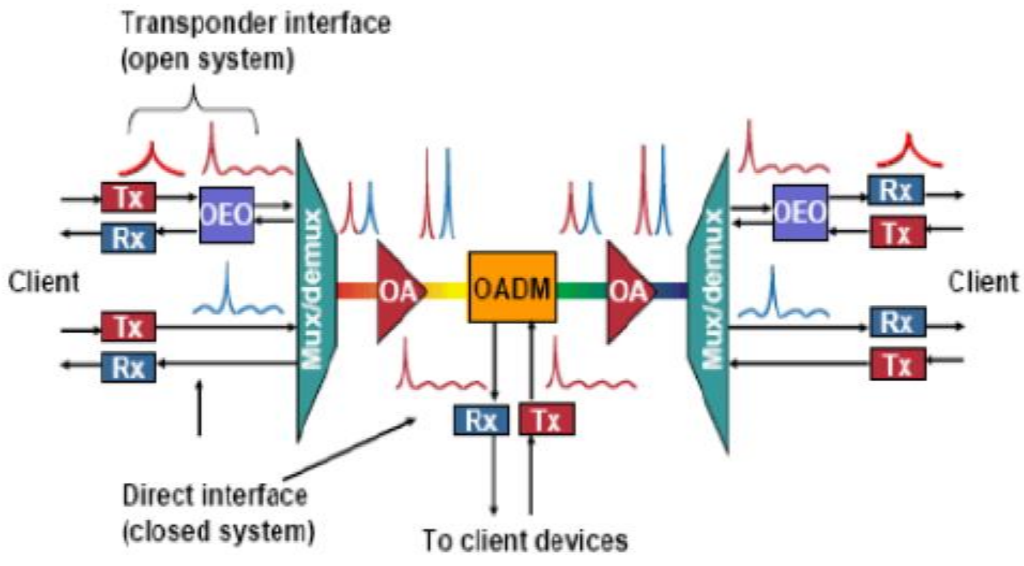


Figure 2.7 DWDM technique in its most basic representation [13].

- The transponder accepts input in the form of a single mode or multimode laser pulse. The input can come from different physical media and different protocols and traffic types.
- The wavelength of the transponder input signal is mapped to a DWDM wavelength.
- DWDM wavelengths from the transponder are multiplexed with signals from the direct interface to form a composite optical signal which is launched into the fiber.
- A post-amplifier boosts the strength of the optical signal as it leaves the multiplexer.
- An OADM is used at a remote location to drop and add bit streams of a specific wavelength.
- Additional optical amplifiers can be used along the fiber span (line amplifier) when needed.
- A pre-amplifier boosts the signal before it enters the demultiplexer.
- The incoming signal is demultiplexed into individual DWDM wavelengths.
- The individual DWDM wavelengths are either mapped to the required output type through the transponder or they are passed directly to the client-side equipment.

2.3.3 DWDM advantages and disadvantages

a. Advantages

- Unlimited transmission capacity due to multi-data transmission network.
- Flexible as it is a protocol and bit rate independent.
- Expanded at any node very smoothly.
- Data transparency and high reliability.

- Suitable for long haul transmission.
- Continuous data regeneration is not required.

b. Disadvantages

- Amplifiers are used to improve power and gain thus system becomes expensive.
- Since multiple optical signals are multiplexed together thus insertion loss occurs.
- Splicing and connector losses are also observed which affect the system performance.
- Loss due to chromatic dispersion and polarization dispersion also affect the system.
- Attenuation loss due to impurities in core or cladding of fiber.
- Noise caused by crosstalk phenomena which results in system degradation.

2.3.4 Dispersion compensation techniques

In general, transmission loss, non-linear effects and dispersion are the three main problems in optical fiber communication system. Especially in the case of long-haul and ultra-long haul transmission systems, their effect is cumulative over the length of fiber. With the introduction of erbium doped fiber amplifier (EDFA) the problem of transmission loss has been solved and, the nonlinear effects can also be suppressed by working at suitable power levels and introducing some dispersion.

Now dispersion becomes the only main obstacle for enhancing capacity and upgrading optical fiber communication system. The first option to mitigate it was the use of dispersion shifted fibers (DSFs) that differ from the standard fibers by shifting the zero dispersion point from 1310 nm to 1550 nm by constructing a single mode fiber with a triangular-shaped refractive index variation. However, this technique is sensitive to four-wave mixing (FWM) and hence not efficient for WDM and dense wavelength division multiplexing (DWDM) systems.

To overcome the problem of four-wave mixing, a nonzero dispersion-shifted fiber (ITU-T G.655) is produced having a zero-dispersion wavelength outside the 1550 nm operating window. The practical effect of this is to have a small but finite amount of chromatic dispersion at 1550 nm, which minimizes the nonlinear effect. There are two fiber families called nonzero dispersion (NZD+ and NZD-), in which the zero-dispersion value falls before and after the 1550 nm wavelength, respectively. Though the problem of FWM is solved, a dispersion compensation technique is necessary; especially for high-speed and long distance G.655 fiber systems [14].

Various methods of chromatic dispersion compensation techniques have been proposed including Dispersion Compensation Fiber (DCF), Electronic Dispersion Compensation

(EDC), Fiber Bragg Grating (FBG), Optical Phase Conjugation (OPC) and digital filters. The most widely utilized techniques are DCF and FBG.

2.3.4.1 Dispersion Compensation Fiber (DCF)

DCF is a loop of fiber having negative dispersion equal to the dispersion of the transmitting fiber. The positive dispersion of standard mode fiber in C and L band can be compensated by using dispersion compensating fiber having high values of negative dispersion -70 to -90 ps/nm.km.

A DCF module should have low insertion loss, low polarization mode dispersion and low optical non-linearity. In addition to these characteristics DCF should have large chromatic dispersion coefficient to minimize the size of a DCF module. By placing one DCF with negative dispersion after a SMF with positive dispersion, the net dispersion will be zero. The perfect condition for dispersion compensation is expressed by equation 2.1:

$$D_{SMF} \times L_{SMF} = -D_{DCF} \times L_{DCF} \tag{2.1}$$

Where D and L are the dispersion and length of each fiber segment respectively [15].

Depending on the arrangement of SMF and DCF in the link, fiber based compensation is done by three methods:

- **Pre-compensation:** in which DCF is placed before SMF.
- **Post-compensation**: in which DCF is placed after SMF.
- **Symmetrical-compensation:** in which DCF is positioned between two equal lengths of SMF.

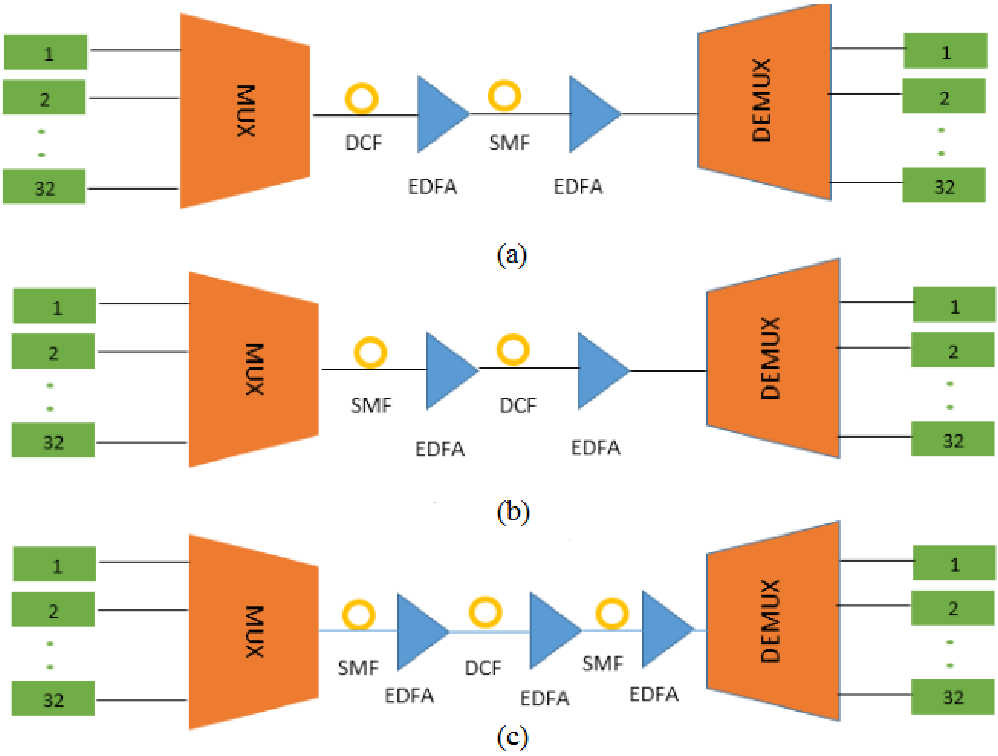


Figure 2.8 Different methods of DCF

(a) Pre (b) Post (c) Symmetrical compensation [16].

2.3.4.2 Fiber Bragg Grating (FBG)

FBG is a section of optical fiber with a periodic variation of the core refractive index along the grating length. Because of this feature, the grating acts as an optical filter. More specifically, it develops a stop band in the form of a spectral region over which some of the incident light is reflected back. The stop band is centered at the Bragg wavelength λ_B that is related to the grating period by the relation

$$\lambda_B = 2n\Lambda \tag{2.2}$$

Where λ_B, n and Λ are the Bragg wavelength, the refractive index of the core and the grating period respectively. Light signals at wavelengths other than the Bragg wavelength, which are not phase matched, are essentially transparent and will be transmitted [33]. This is shown in figure 2.9.

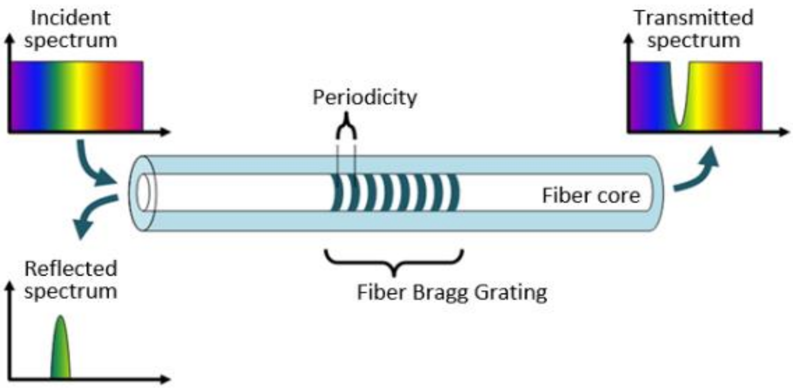


Figure 2.9 Spectral response of FBG [34].

The most common advantage of FBG is the low insertion loss (IL). Typically, a 120 km FBG-DCM has an insertion loss in the range of 3 to 4 dB, depending on the type. Furthermore, the FBG-DCM does not introduce any nonlinear effect even at the highest power levels present throughout an optical network.

A comparative study between DCF and FBG is summarized in Table 2.3.

Table 2.3 Comparison between DCF and FBG.

Characteristics	DCF	FBG
Bandwidth	Wide band, 20 nm	Narrow band, 0.1-5 nm
Fiber length	17-20 km	10-15 cm
Construction	Complex	Simple
negative dispersion	−80 to −120 ps/nm/km	-2000 ps/nm/km
positive dispersion	+15 to +25 ps/nm/km	+2000 ps/nm/km
Dispersion	16 ps/nm /km	17 ps/nm/km
Bending loss	0.4-0.6 dB/km	0.14 dB/km
Reflectance ratio	99.99%	10-95%
Attenuation	0.8 dB/km	0.2 dB/km
Nonlinear effects	Some limitations	No
Insertion loss	High	Low
Overall Cost of system	High	Low

2.4 Parameters affecting the system design

When designing a fiber optic system, there are many factors that must be considered, all of which contribute to the final goal of ensuring that enough light reaches the receiver. But the most important parameters that must be taken into account are: optical signal to noise ratio, Q factor and bit error rate of the system.

2.4.1 Optical signal to noise ratio (OSNR)

OSNR is a measure of the ratio of optical signal level to the system noise level. Signal strength reduces over distance in an optical fiber and may need boosting periodically with optical amplifiers. The optical gain associated with these amplifiers must be balanced against the additional noise each amplifier introduces. The weaker the signal level or the greater the noise level leads to a lower OSNR. Receivers require acceptable levels of OSNR to distinguish signals from system noise. As OSNR decreases, bit detection and recovery errors increase. OSNR is measured in decibels (dB) [13].

2.4.2 Q factor

The Q factor is a parameter that provides a qualitative description of the receiver performance. It measures the quality of a transmission signal in terms of its optical signal to noise ratio (OSNR). It takes into account physical impairments of the signal like noise, chromatic dispersion and any polarization or non-linear effects, which can degrade the signal and ultimately cause bit errors [17]. The higher the value of Q, the better the quality of the system.

The logarithmic value of Q as a function of OSNR is given by the equation:

$$Q_{dB} = 20log\sqrt{OSNR}\sqrt{\frac{B_0}{B_c}} \tag{2.3}$$

Where B_0 and B_c are the optical bandwidth of the end device (photodetector) and the electrical bandwidth of the receiver filter respectively. In other words, Q is proportional to the OSNR. Generally, noise measurements are performed by optical spectrum analyzers (OSAs) or sampling oscilloscopes.

2.4.3 Bit Error Rate (BER)

The BER is one of the main parameters describing the quality of the data link. It is defined as the percentage of erroneous bits relative to the total number of bits received in a transmission. It is given by the following equation:

$$BER = \frac{n}{N} \tag{2.4}$$

Where n is the number of erroneous bits received and N is the total number of bits received in the defined time interval [17].

In the case of WDM networks, the requirement of BER is about 10^{-12}(10^{-9} to 10^{-12}), which means that a maximum of one out of every 10^{12} bits can be corrupted during transmission.

The bit error rate is related to the Q factor by the following equation:

$$BER = \frac{1}{2} erfc(\frac{Q}{\sqrt{2}}) \quad (2.5)$$

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

$$erfc(x) = 1 - erf(x) \quad (2.6)$$

erf is the error function defined as:

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\, dt \quad (2.7)$$

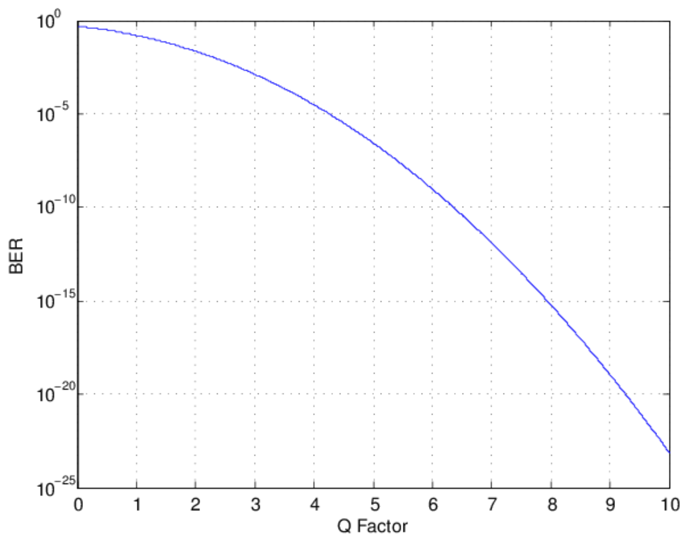


Figure 2.10 BER versus Q factor [18].

From figure 2.10, it is clearly seen that as the Q factor increases, the BER decreases providing a good quality of signal.

2.5 Conclusion

DWDM with its main characteristics and the system components have been discussed. It is clear that DWDM will definitely reshape the future communication network as it has bandwidth availability which is the need of hour. Various advantages of DWDM make it the ideal technology for communication systems.

3.1 Introduction

In this chapter, an eight channel DWDM point-to-point topology network will be simulated using Optisystem v.7.0 software. This topology is provided by Djezzy Company. It connects two sites separated by 0.695 km: Djezzy Academy and El- Mouradia as illustrated in figure 3.1.

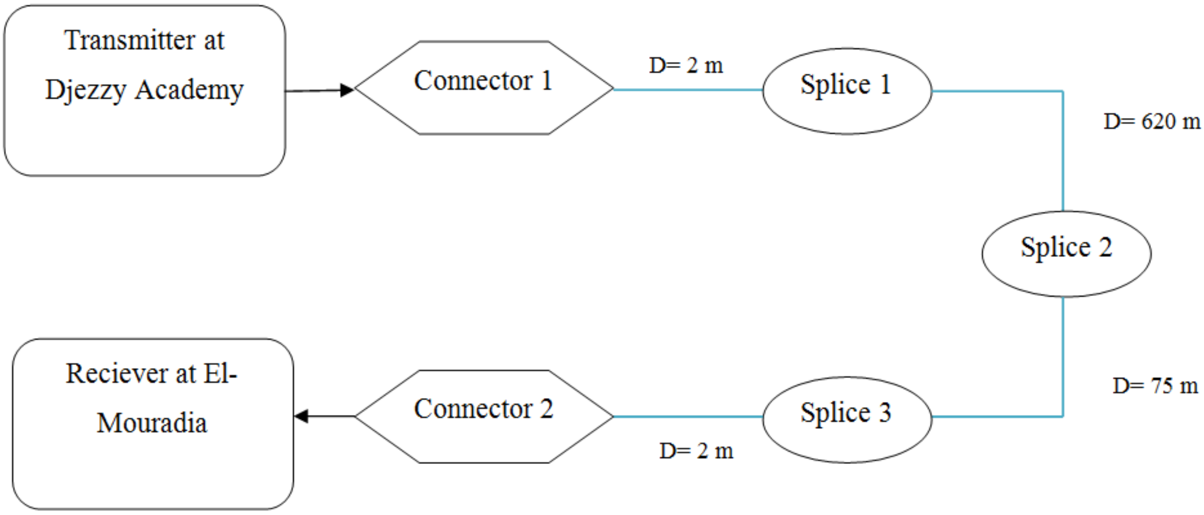


Figure 3.1 Block diagram of a DWDM line topology network.

The goal of this simulation is to study the effect of the bit rate, the input power and dispersion compensation techniques on the DWDM system performance. Hence, this system will be simulated first without dispersion compensation at three different operating bit rates: 30, 60 and 90 Gbps by varying the input power in the range of –30 up to 30 dBm. Then, to overcome pulse degradation DCF and FBG pre and post compensation are modeled, analyzed and compared to investigate the performance of DWDM system. Further, the results are explored in terms of eye-diagram, BER and Q factor.

3.2 Overview on Optisystem

Optisystem is an optical communication system simulation package that enables users to plan, test and simulate almost every type of optical link in the physical layer of a broad spectrum of optical networks, it is a system level simulator based on the realistic modeling of fiber optic communication systems.

Applications

- Optical communication system design from component to system level at the physical layer.
- TDM/WDM network design.
- 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.

3.3 Description of system structure

A basic optical communication system consists of an externally modulated transmitter, an optical link and a receiver.

3.3.1 Externally modulated subsystem (EMS)

To fully exploit the usefulness of fiber optic links, an externally modulated subsystem is used to generate a signal which can be displayed by either BER analyzer or eye diagram analyzer. EMS consists of:

- Pseudo random bit sequence (PRBS) generator
- NRZ pulse generator
- Mach Zehnder modulator

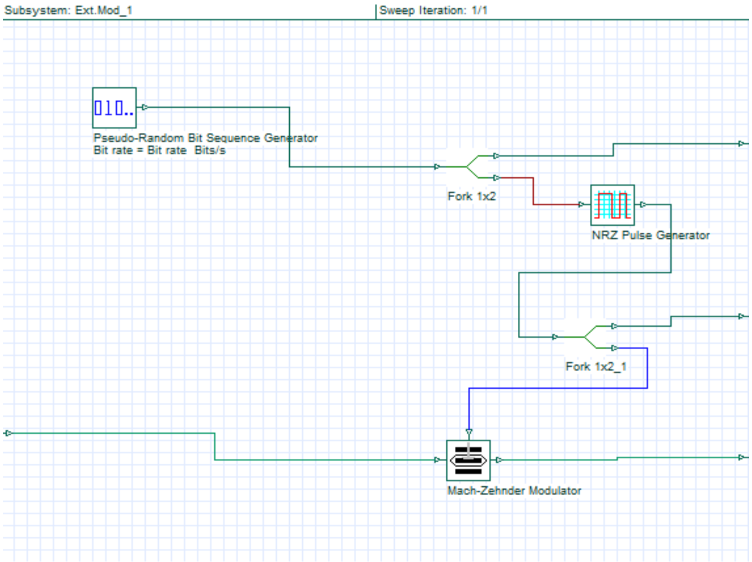
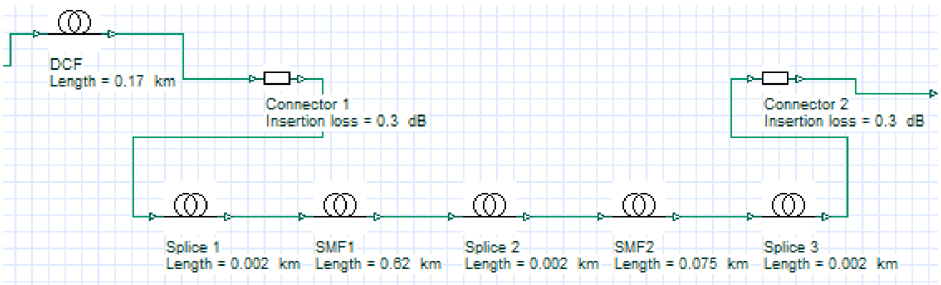


Figure 3.2 Externally Modulated Transmitter with three output ports.

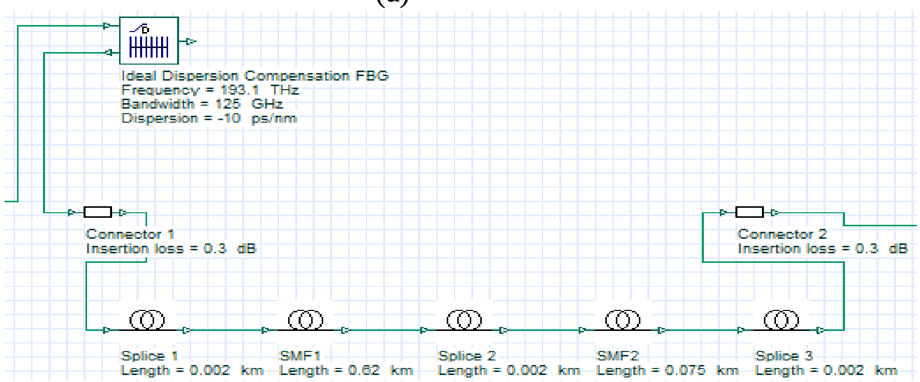
3.3.2 Optical link

It connects between the multiplexer and demultiplexer. Figure 3.3 shows the components composing the optical link:

- **Single mode fiber (SMF):** The optical fiber used is SMF because it can yield high data rates and less dispersion. The most important parameters in the fiber are: Length, attenuation, dispersion, dispersion slope, and PMD coefficient. The parameters chosen for the SMF are extremely important, and will significantly affect the simulation results.
- **Splice:** It results from joining two fiber optic cables together. In this case, fusion splices are used and they are modeled as lossy fibers having an attenuation of 0.1 dB/km.
- **Connector:** An optical fiber connector terminates the end of an optical fiber, and enables quicker connection and disconnection than splicing. The connectors mechanically couple and align the cores of fibers so light can pass.
- **Dispersion compensation module:** To compensate for the chromatic dispersion, a dispersion compensation module is used, either DCF or FBG.



(a)



(b)

Figure 3.3 Optical link design

(a) using DCF (b) using FBG.

3.3.3 The receiver implementation

It is composed of: BER analyzer, PIN Photodetector and low pass Bessel filter. As shown in figure 3.4.

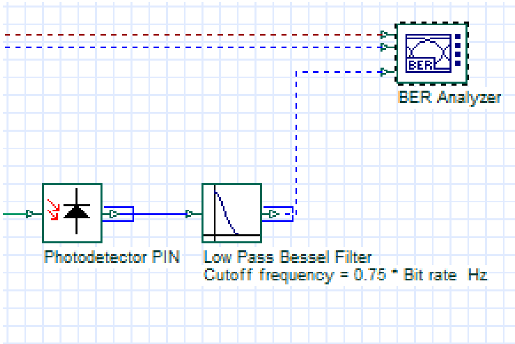


Figure 3.4 The receiver implementation.

The entire system design is illustrated in figure 3.5.

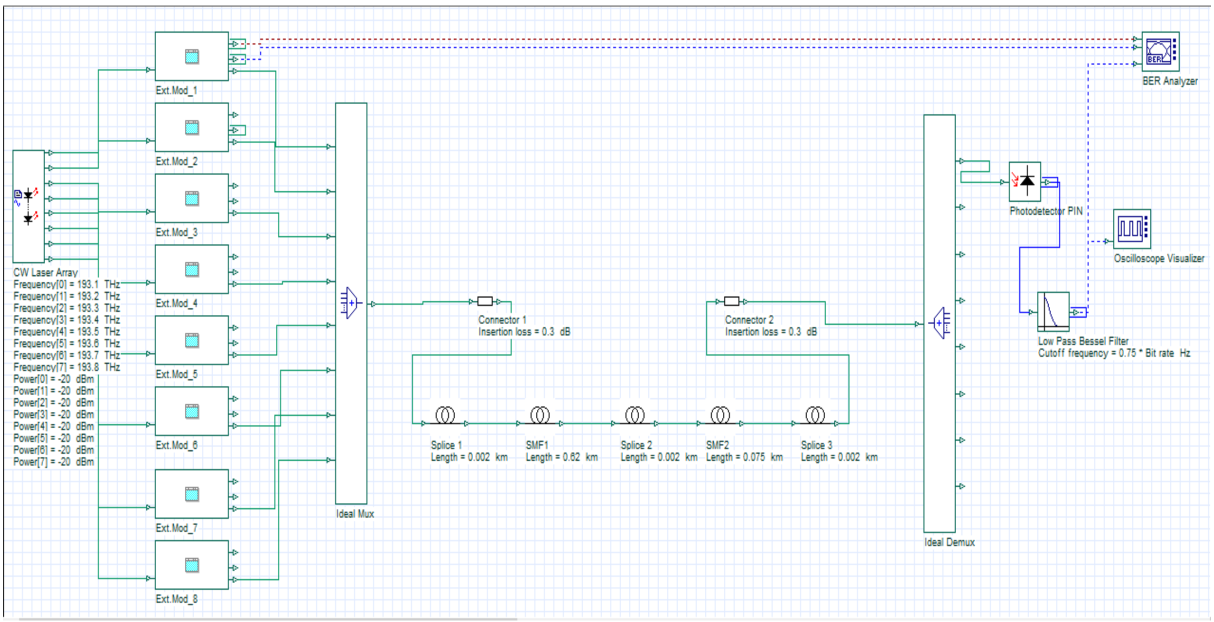


Figure 3.5 The system design.

3.4 Simulation

Dispersion reduction techniques were studied only for channel 1 having a frequency of 191.1 THz, operating at 1550 nm window with 100 GHz frequency spacing at various input power levels ranging from –30 dBm to 30 dBm for the three different bit rates 30, 60 and 90 Gbps.

3.4.1 Pre- and Post-compensation by using DCF

In our system configuration, splices are presented as SMFs having a similar dispersion and an attenuation of 0.1 dB/km, this makes the dispersion parameter of SMF 0.701 km long instead of 0.695 km with D=17 ps/nm/km. Based on equation 2.1, this dispersion can be compensated by using a 0.17 km long DCF with -70 ps/km/nm dispersion.

Table 3.1 System parameters.

Parameter	Value
Bit rate	30, 60 and 90 Gbps
Wavelength	1550 nm
Length of SMF1	0.62 km
Length of SMF2	0.075 km
Length of splices 1, 2 and 3	0.002 km
Length of DCF	0.17 km
Dispersion of SMF1	17 ps/nm/km
Dispersion of SMF2	17 ps/nm/km
Dispersion of splices 1, 2 and 3	17 ps/nm/km
Dispersion of DCF	-70 ps/nm/km
Attenuation of SMF1	0.22 dB/km
Attenuation of SMF2	0.22 dB/km
Attenuation of splices 1, 2 and 3	0.1 dB/km
Attenuation of DCF	0.5 dB/km
Insertion loss of connectors 1 and 2	0.3 dB

In the pre-compensation case, DCF is placed before the first connector, whereas in the post-compensation case DCF is placed after the second connector as shown in figures 3.6 and 3.7 respectively.

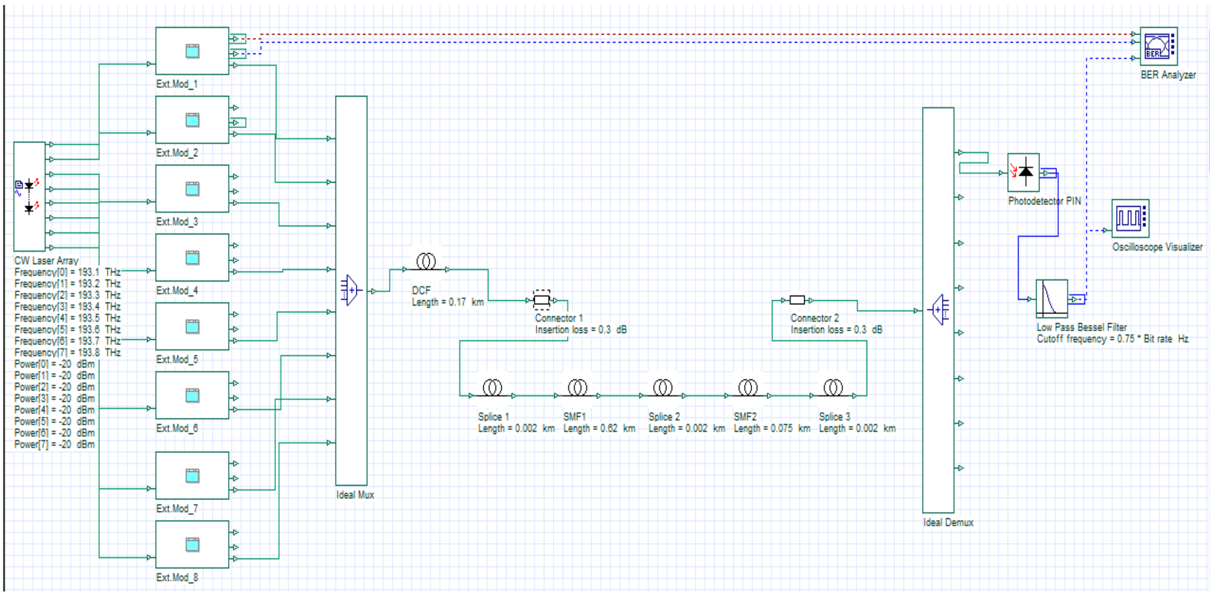


Figure 3.6 Dispersion pre-compensation design using DCF.

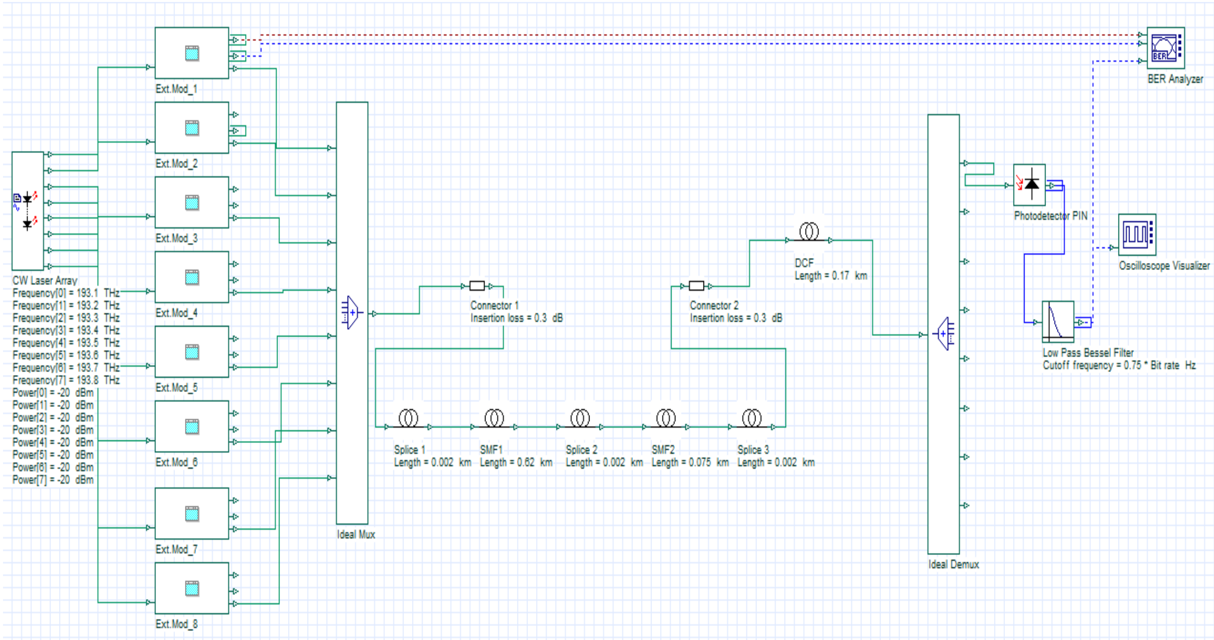


Figure 3.7 Dispersion post-compensation design using DCF.

3.4.2 Simulation results

Q factor and BER simulation results for 30, 60 and 90 Gbps are summarized in the following tables.

Table 3.2 Simulation Results for the System at 30 Gbps using DCF.

Input power (dBm)	Without compensation		Pre-compensation		Post-compensation	
	Q	BER	Q	BER	Q	BER
-30	0	1	0	1	0	1
-25	0	1	5.18	$1.05e^{-7}$	5.24	$7.63e^{-8}$
-20	0	1	15.66	$2.57e^{-55}$	15.79	$1.81e^{-56}$
-15	0	1	37.88	$2.14e^{-314}$	38.14	$1.33e^{-318}$
-10	0	1	56.96	0	57.07	0
-5	0	1	62.46	0	62.49	0
0	0	1	63.58	0	63.49	0
5	0	1	63.45	0	63.52	0
10	0	1	63.11	0	63.12	0
15	0	1	62.68	0	62.68	0
20	0	1	55.56	0	55.57	0
25	0	1	30.77	$1.89e^{-208}$	30.66	$6.14e^{-207}$
30	0	1	10.98	$1.38e^{-28}$	10.80	$1.08e^{-27}$

Table 3.3 Simulation Results for the System at 60 Gbps using DCF.

Input power (dBm)	Without compensation		Pre-compensation		Post-compensation	
	Q	BER	Q	BER	Q	BER
-30	0	1	0	1	0	1
-25	0	1	3.11	$9.21e^{-4}$	3.13	$8.42e^{-4}$
-20	0	1	5.95	$1.15e^{-9}$	5.98	$9.81e^{-10}$
-15	0	1	7.80	$2.14e^{-15}$	7.81	$1.96e^{-15}$
-10	0	1	8.43	$1.09e^{-17}$	8.43	$1.07e^{-17}$
-5	0	1	8.57	$3.16e^{-18}$	8.57	$3.16e^{-18}$
0	0	1	8.59	$2.62e^{-18}$	8.60	$2.44e^{-18}$
5	0	1	8.62	$2.00e^{-18}$	8.62	$1.94e^{-18}$
10	0	1	8.65	$1.55e^{-18}$	8.65	$1.57e^{-18}$
15	0	1	8.75	$6.50e^{-19}$	8.75	$6.50e^{-19}$
20	0	1	9.04	$4.80e^{-20}$	9.04	$4.73e^{-20}$
25	0	1	9.48	$7.67e^{-22}$	9.50	$6.63e^{-22}$
30	0	1	4.72	$8.91e^{-7}$	4.62	$1.40e^{-6}$

Table 3.4 Simulation Results for the System at 90 Gbps using DCF.

Input power (dBm)	Without compensation		Pre-compensation		Post-compensation	
	Q	BER	Q	BER	Q	BER
-30	0	1	0	1	0	1
-25	0	1	0	1	0	1
-20	0	1	2.37	$6.24e^{-3}$	2.38	$6.15e^{-3}$
-15	0	1	2.64	$2.45e^{-3}$	2.64	$2.44e^{-3}$
-10	0	1	2.72	$1.75e^{-3}$	2.72	$1.74e^{-3}$
-5	0	1	2.74	$1.60e^{-3}$	2.74	$1.60e^{-3}$
0	0	1	2.75	$1.58e^{-3}$	2.75	$1.58e^{-3}$
5	0	1	2.75	$1.58e^{-3}$	2.75	$1.58e^{-3}$
10	0	1	2.74	$1.59e^{-3}$	2.74	$1.59e^{-3}$
15	0	1	2.74	$1.62e^{-3}$	2.74	$1.62e^{-3}$
20	0	1	2.72	$1.72e^{-3}$	2.72	$1.72e^{-3}$
25	0	1	2.66	$2.07e^{-3}$	2.66	$2.07e^{-3}$
30	0	1	2.57	$3.35e^{-3}$	2.57	$3.38e^{-3}$

3.4.3 Discussion

In order to facilitate the analysis of the system performance, the Q factor versus the input power is plotted for channel 1 at 30, 60 and 90 Gbps.

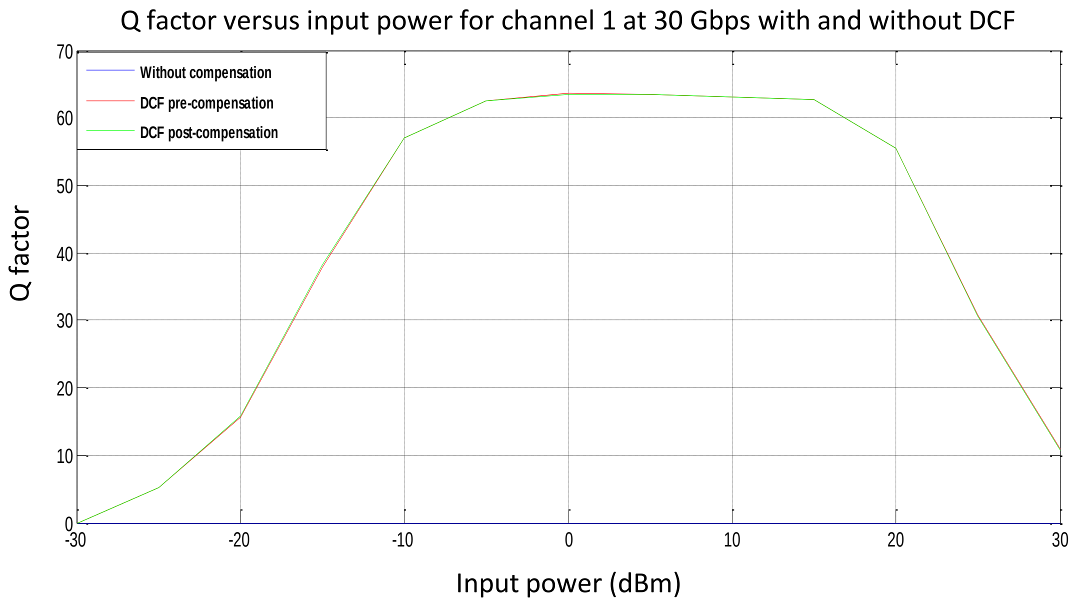


Figure 3.8 Q factor versus input power for channel 1 at 30 Gbps with and without DCF.

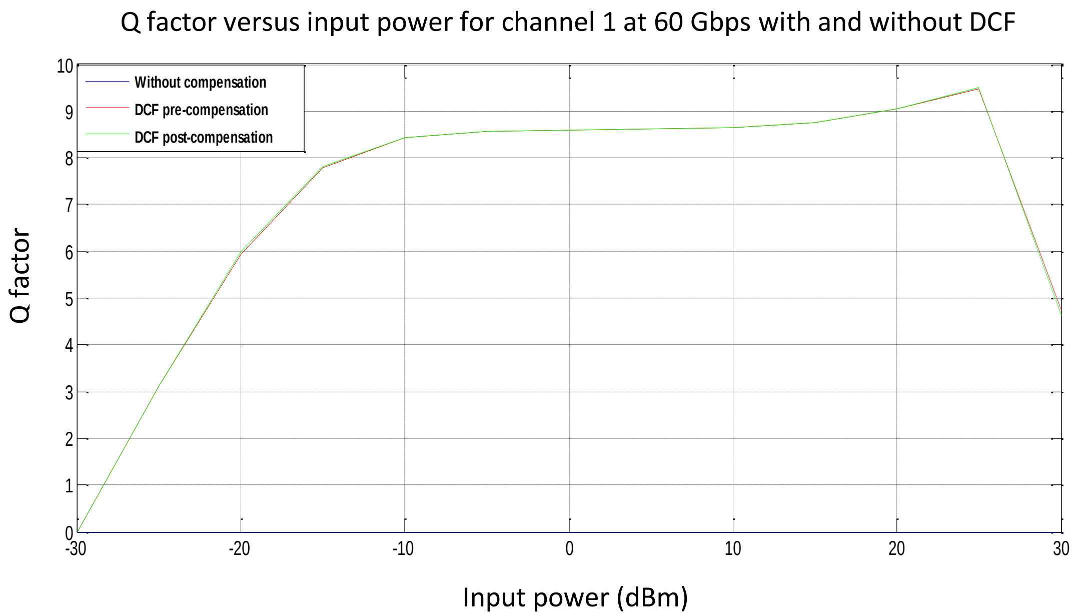


Figure 3.9 Q factor versus input power for channel 1 at 60 Gbps with and without DCF.

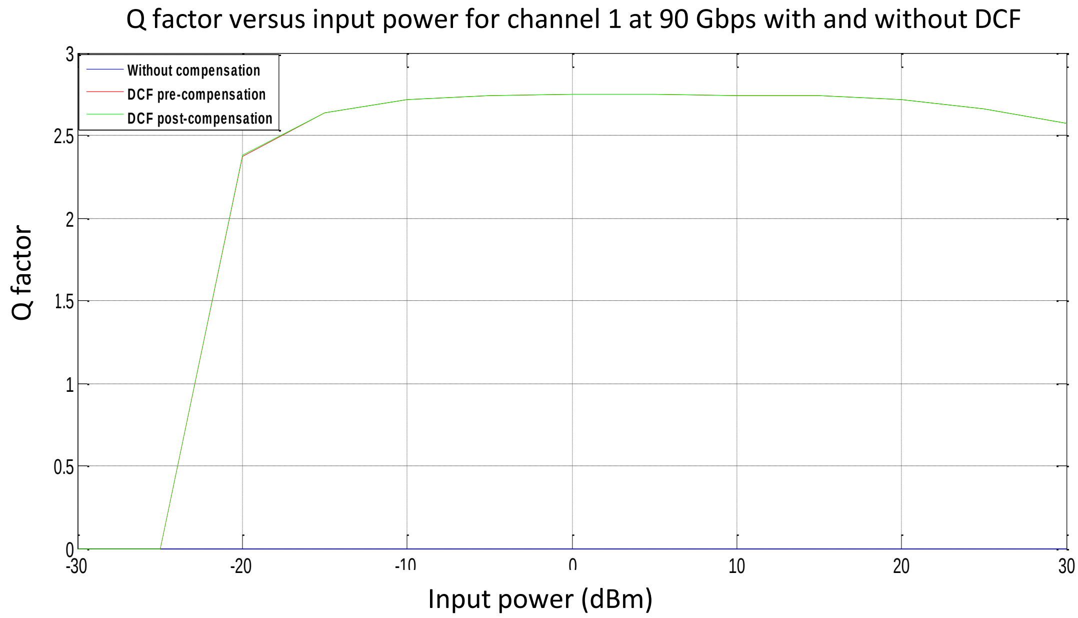


Figure 3.10 Q factor versus input power for channel 1 at 90 Gbps with and without DCF.

The graphs of figures 3.8 to 3.10 represent the Q factor versus the input power for channel 1 at 30, 60 and 90 Gbps respectively for the conventional case, DCF pre- and post-compensation.

- **At 30 Gbps**

  For the conventional case, it is noticed that the Q factor is zero which indicates the bad performance of the system, but when using DCF it becomes better. The Q factor keeps increasing until it reaches its maximum 63.58 at 0 dBm for the pre-compensation and 63.52 at 5 dBm for the post-compensation. After reaching the maximum, the Q factor starts decreasing.

- **At 60 Gbps**

  It is clearly observed that the system performance is bad when no compensation technique is used. From -30 to 25 dBm, both pre- and post- compensations provide better results. The maximum Q factor is 9.48 and 9.50 at P_{in}= 25 dBm for pre- and post- compensations respectively. Beyond 25 dBm, the Q factor decreases.

- **At 90 Gbps**

  The Q factor is zero for the conventional case for the whole range of power. When using both DCF pre- and post-compensations, it is observed that the system performance is bad for $P_{in} = [-30, -25]$ dBm. Then, the Q factor starts increasing until it reaches its maximum 2.75 at 5 dBm for both techniques. After 5 dBm, the Q factor decreases.

Table 3.5 Eye diagram results obtained before and after using DCF at 30 Gbps.

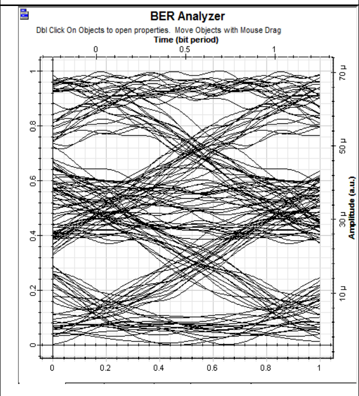
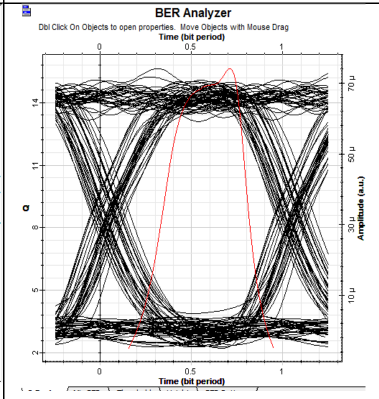
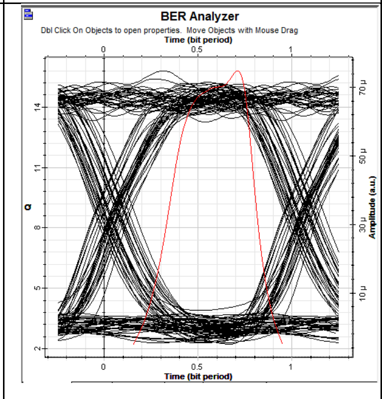
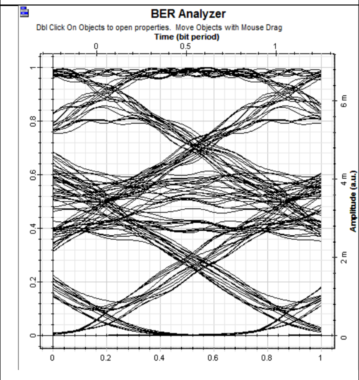
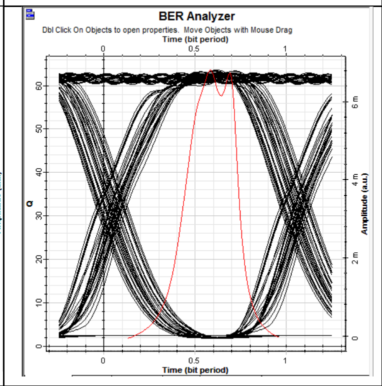
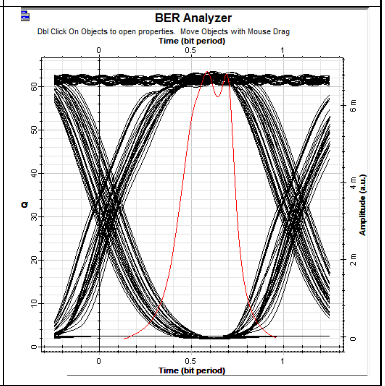
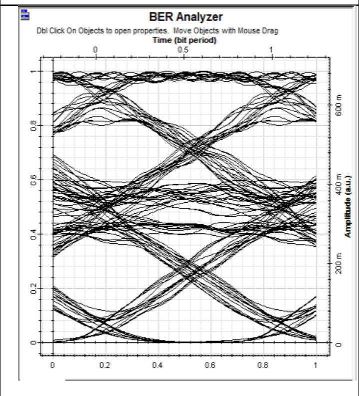
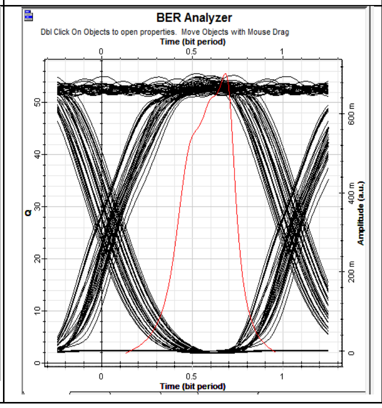
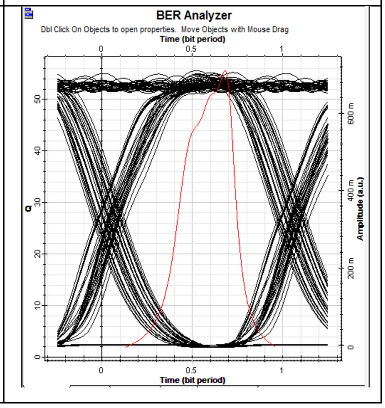
	30 Gbps		
	Without compensation	**Pre-compensation**	**Post-compensation**
-20 dBm			
0 dBm			
20 dBm			

Table 3.6 Eye diagram results obtained before and after using DCF at 60 Gbps.

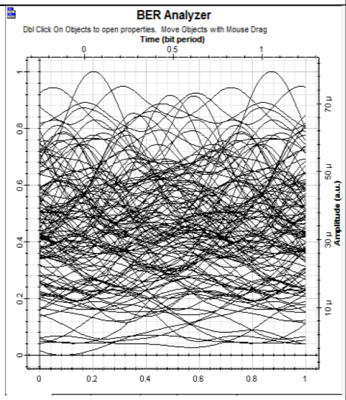
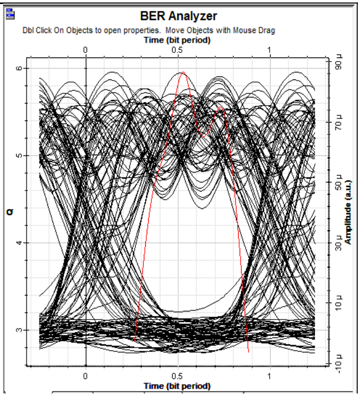
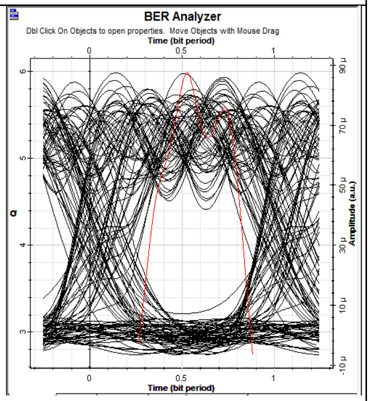
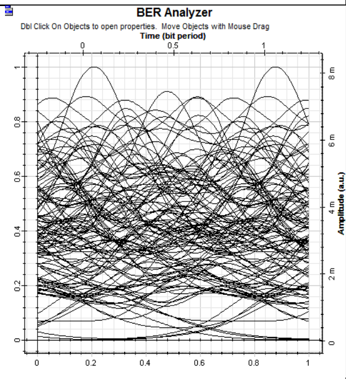
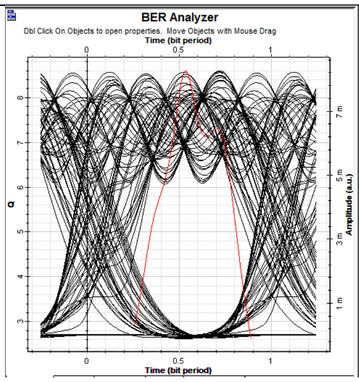
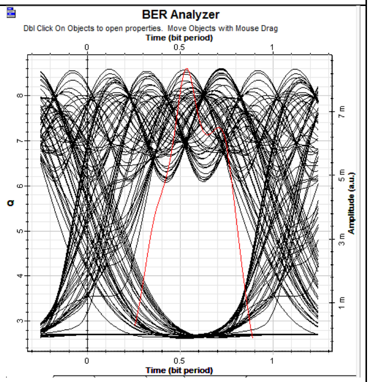
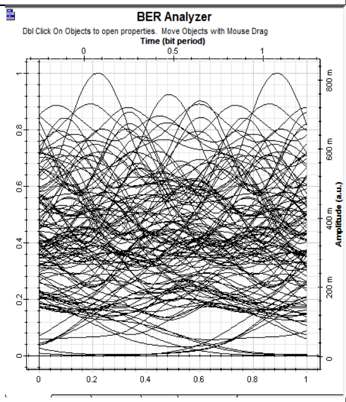
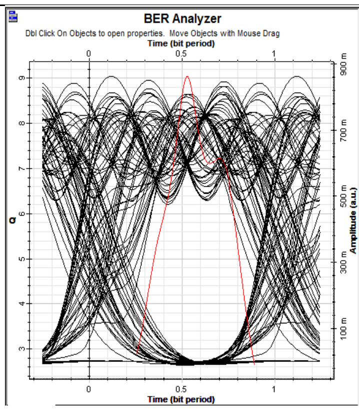
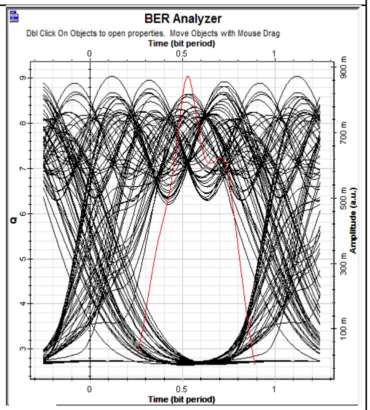
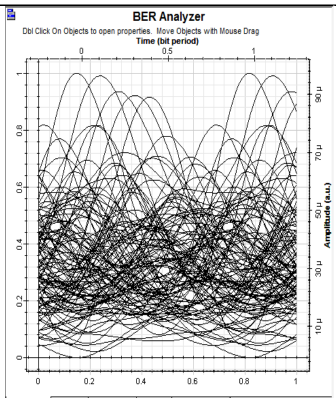
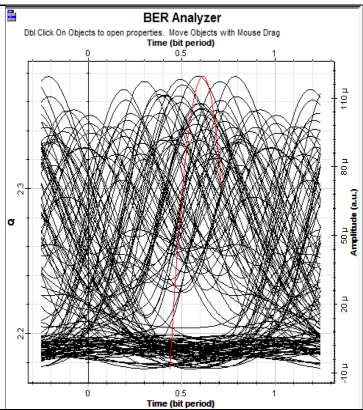
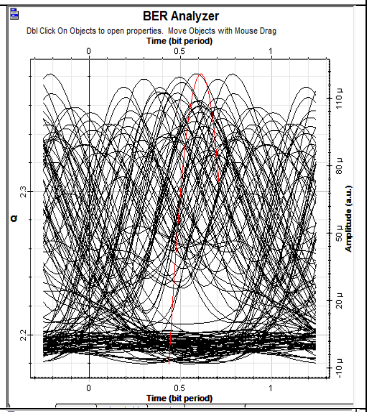
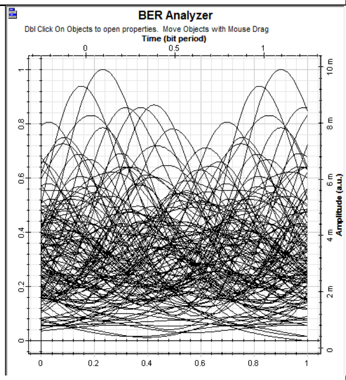
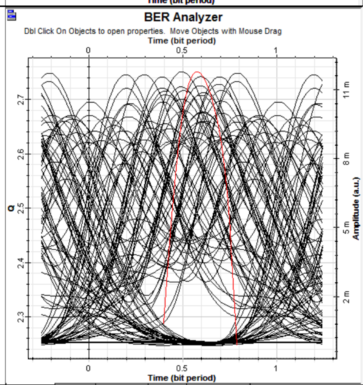
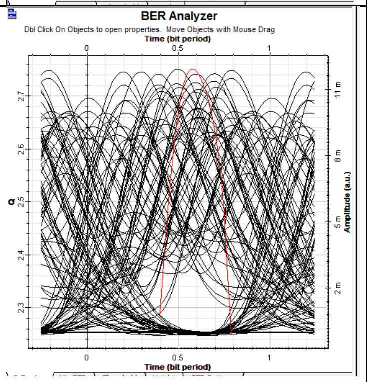
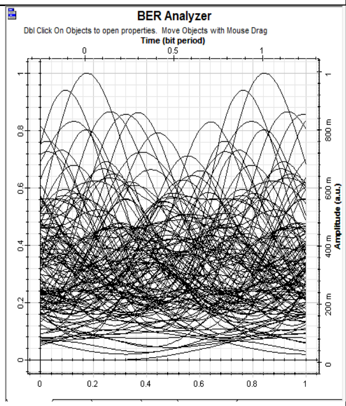
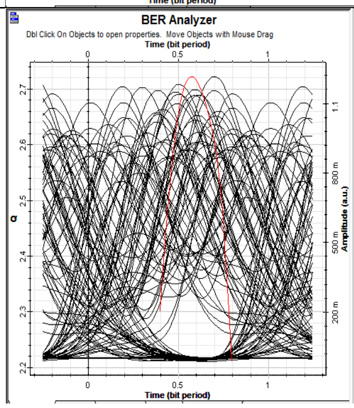
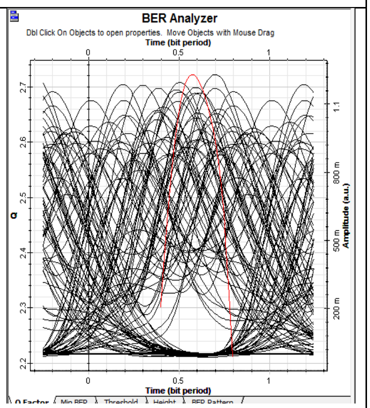
	60 Gbps		
	Without compensation	**Pre-compensation**	**Post-compensation**
-20 dBm			
0 dBm			
20 dBm			

Table 3.7 Eye diagram results obtained before and after using DCF at 90 Gbps.

	90 Gbps		
	Without compensation	**Pre-compensation**	**Post-compensation**
-20 dBm			
0 dBm			
20 dBm			

- **At 30 Gbps**

  It is seen from table 3.5 that there is a distortion in the signal for all values of input power for the conventional case, specially at -20 dBm. Whereas using DCF, yield to a widely open eye diagram for both pre- and post-compensations, especially at $P_{in} = 0$ dBm.

- **At 60 Gbps**

  According to table 3.6, the signal is severly distorted for all input powers when no compensation technique is used. However, both pre- and post-compensations provide an open eye diagram when DCF is used.

- **At 90 Gbps**

  From table 3.7, it is observed that the system performance is very bad with and without compensation techniques.

3.4.4 Pre- and Post-compensation by using FBG

Now an ideal dispersion compensation FBG is applied with a total dispersion of -10 ps/nm. In the pre-compensation case, FBG is placed before the first connector, whereas in the post-compensation case FBG is placed after the second connector as shown in figures 3.11 and 3.12 respectively.

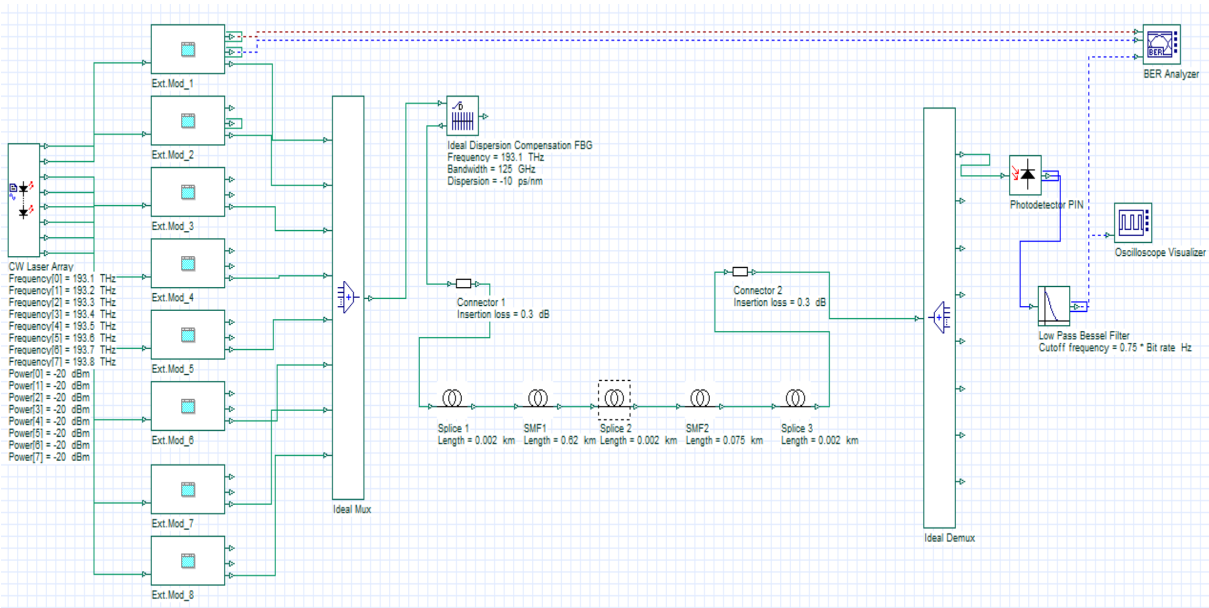


Figure 3.11 Dispersion pre-compensation design using FBG.

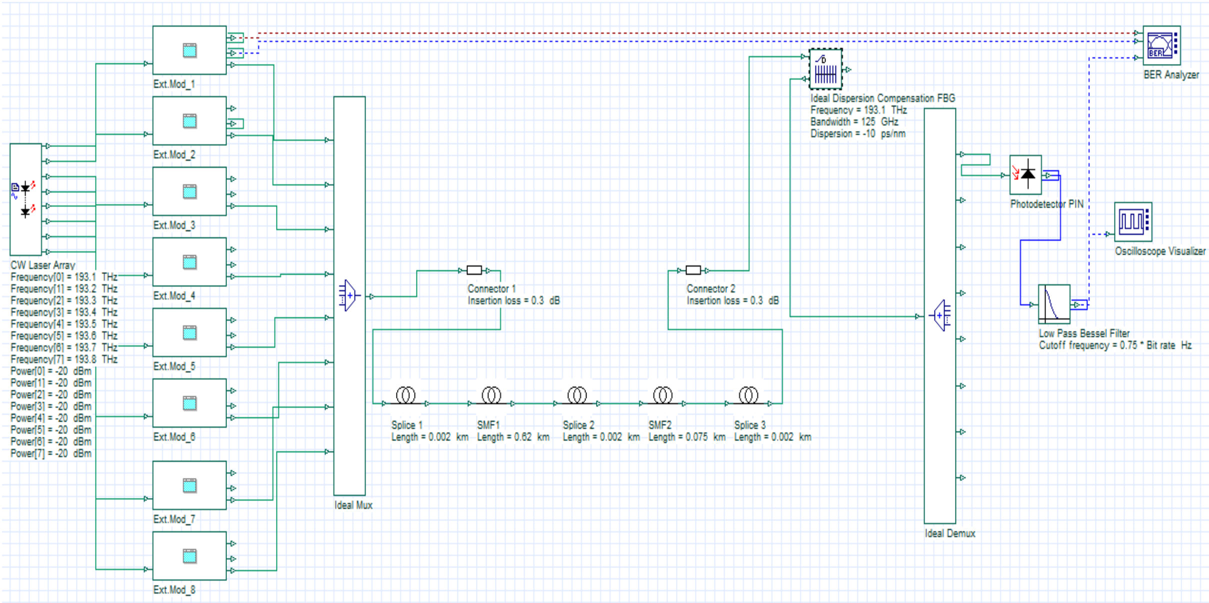


Figure 3.12 Dispersion post-compensation design using FBG.

3.4.5 Simulation results

The results of Q factor and BER simulation for 30, 60 and 90 Gbps are shown in the following tables.

Table 3.8 Simulation Results for the System at 30 Gbps using FBG.

Input power (dBm)	Without compensation		Pre-compensation		Post-compensation	
	Q	BER	Q	BER	Q	BER
-30	0	1	0	1	0	1
-25	0	1	0	1	0	1
-20	0	1	2.02	$2.11e^{-2}$	2.03	$2.11e^{-2}$
-15	0	1	6.33	$1.22e^{-10}$	6.33	$1.22e^{-10}$
-10	0	1	18.94	$2.34e^{-80}$	18.94	$2.52e^{-80}$
-5	0	1	42.64	0	42.56	0
0	0	1	56.70	0	57.02	0
5	0	1	59.93	0	60.67	0
10	0	1	60.83	0	59.99	0
15	0	1	61.25	0	43.14	0
20	0	1	61.53	0	17.47	$7.34e^{-69}$
25	0	1	61.79	0	5.05	$1.20e^{-7}$
30	0	1	58.34	0	0	1

Table 3.9 Simulation Results for the System at 60 Gbps using FBG.

Input power (dBm)	Without compensation		Pre-compensation		Post-compensation	
	Q	BER	Q	BER	Q	BER
-30	0	1	0	1	0	1
-25	0	1	0	1	0	1
-20	0	1	0	1	0	1
-15	0	1	4.54	$2.69e^{-6}$	4.54	$2.69e^{-6}$
-10	0	1	9.34	$4.37e^{-21}$	9.33	$4.44e^{-21}$
-5	0	1	11.99	$1.48e^{-33}$	11.97	$1.80e^{-33}$
0	0	1	12.50	$2.49e^{-36}$	12.55	$1.48e^{-36}$
5	0	1	12.55	$1.32e^{-36}$	12.61	$6.22e^{-37}$
10	0	1	12.54	$1.58e^{-36}$	12.71	$1.91e^{-37}$
15	0	1	12.45	$4.84e^{-36}$	12.81	$4.90e^{-38}$
20	0	1	12.13	$2.41e^{-34}$	11.37	$2.12e^{-30}$
25	0	1	11.08	$5.08e^{-29}$	4.36	$1.24e^{-6}$
30	0	1	8.10	$1.60e^{-16}$	0	1

Table 3.10 Simulation Results for the System at 90 Gbps using FBG.

Input power (dBm)	Without compensation		Pre-compensation		Post-compensation	
	Q	BER	Q	BER	Q	BER
-30	0	1	0	1	0	1
-25	0	1	0	1	0	1
-20	0	1	0	1	0	1
-15	0	1	2.96	$1.47e^{-3}$	2.96	$1.47e^{-3}$
-10	0	1	4.39	$4.57e^{-6}$	4.39	$4.57e^{-6}$
-5	0	1	4.77	$6.44e^{-7}$	4.77	$6.42e^{-7}$
0	0	1	4.81	$5.42e^{-7}$	4.81	$5.35e^{-7}$
5	0	1	4.80	$5.60e^{-7}$	4.81	$5.27e^{-7}$
10	0	1	4.78	$5.98e^{-7}$	4.82	$5.02e^{-7}$
15	0	1	4.75	$7.19e^{-7}$	4.84	$4.50e^{-7}$
20	0	1	4.63	$1.27e^{-6}$	4.71	$8.99e^{-7}$
25	0	1	4.24	$7.06e^{-6}$	2.82	$1.79e^{-3}$
30	0	1	3.21	$3.78e^{-4}$	0	1

3.4.6 Discussion

The graphs of the Q factor versus the input power for channel 1 at 30, 60 and 90 Gbps for the conventional case, FBG pre- and post-compensation are shown in figures 3.13, 3.14 and 3.15 respectively.

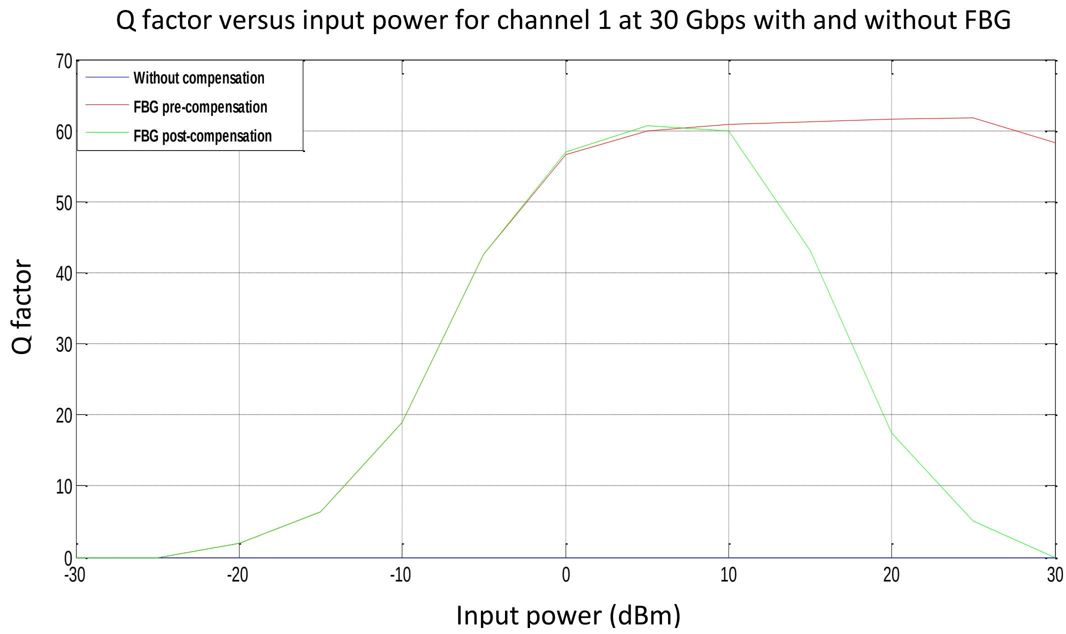


Figure 3.13 Q factor versus input power for channel 1 at 30 Gbps with and without FBG.

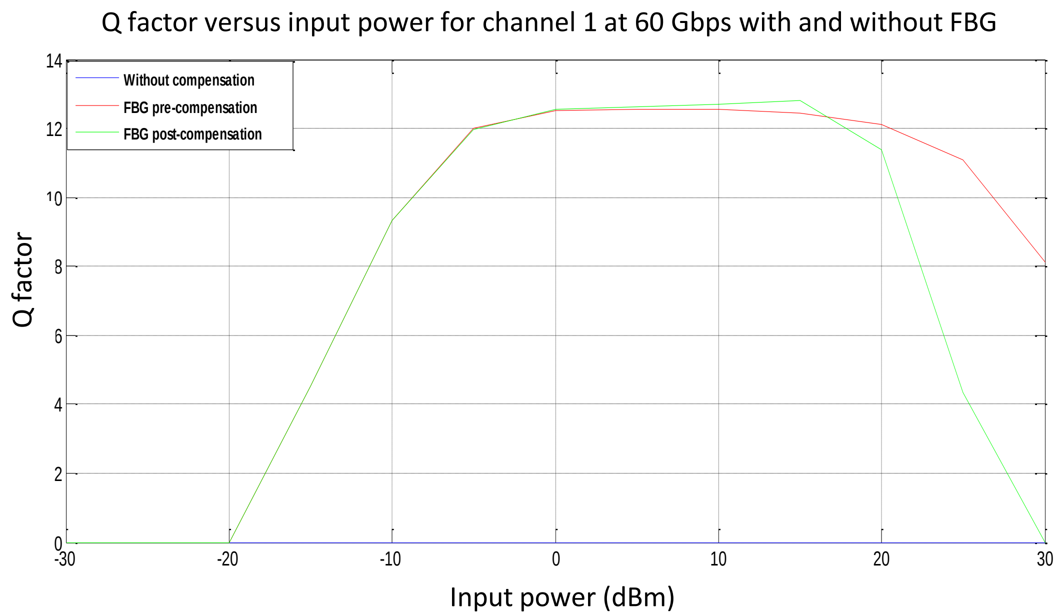


Figure 3.14 Q factor versus input power for channel 1 at 60 Gbps with and without FBG.

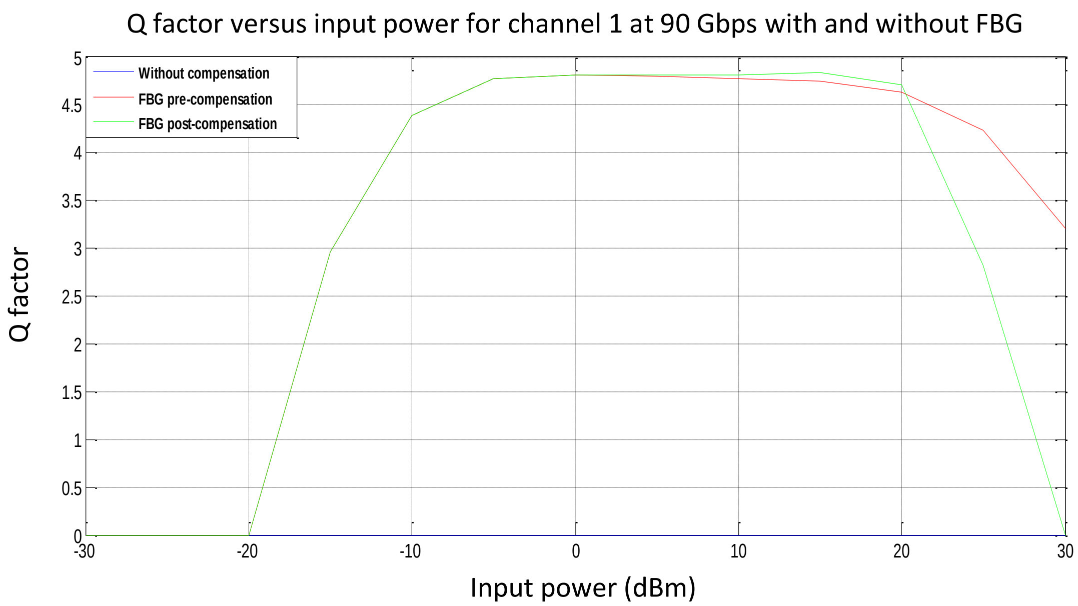


Figure 3.15 Q factor versus input power for channel 1 at 90 Gbps with and without FBG.

- **At 30 Gbps**

  The Q factor is zero for the conventional case for the whole range of power. When using both FBG pre- and post-compensations, it is noticed that the system performance is bad for $P_{in} = [-30, -25]$ dBm. Then, the Q factor starts increasing reaching a maximum of 61.79 at 25 dBm for pre-compensation and 60.67 at 5 dBm for post-compensation. Beyond 25 dBm, the Q factor decreases slightly for pre-compensation, whereas it decreases considerably beyond 5 dBm reaching 0 at 30 dBm for post-compensation, which makes the pre-compensation the preferable technique beyond 5 dBm.

- **At 60 Gbps**

  It is clearly observed that the system performance is bad for all input powers when no compensation technique is used. From -30 to -20 dBm, the Q factor is zero for both FBG pre- and post-compensations. Then, it starts increasing reaching a maximum of 12.55 at 5 dBm for pre-compensation and 12.81 at 15 dBm for post-compensation. Beyond 5 dBm, the Q factor decreases slightly for pre-compensation, while it decreases above 15 dBm to 0 for post compensation at 30 dBm. Thus, when the power exceeds 15 dBm, pre-compensation is better than post.

- **At 90 Gbps**

  The Q factor is zero for the conventional case for all input powers. Both FBG pre- and post-compensations result in a bad system performance for $P_{in} = [-30, -20]$ dBm.

Then, the Q factor starts increasing reaching a maximum of 4.81 at 0 dBm for pre-compensation and 4.84 at 15 dBm for post-compensation. Beyond 0 dBm, the Q factor decreases slightly for pre-compensation, whereas it decreases significantly beyond 15 dBm to 0 for post-compensation at 30 dBm.

Table 3.11 Eye diagram results obtained before and after using FBG at 30 Gbps.

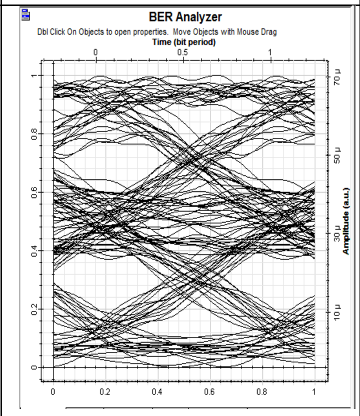
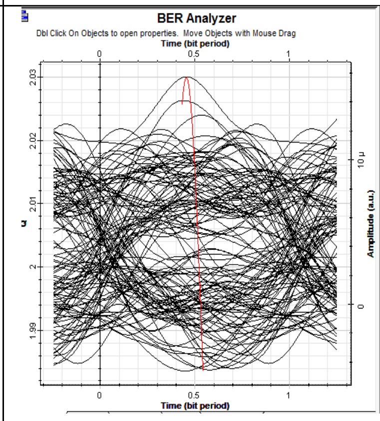
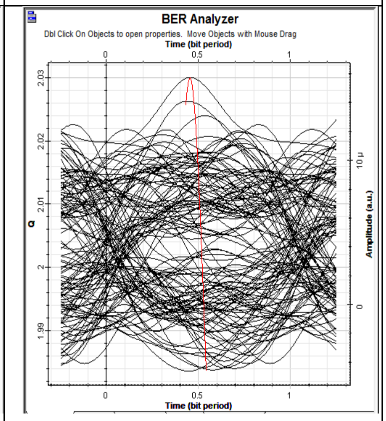
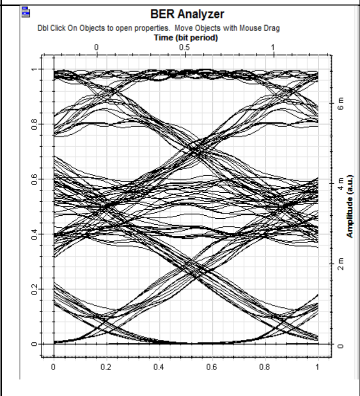
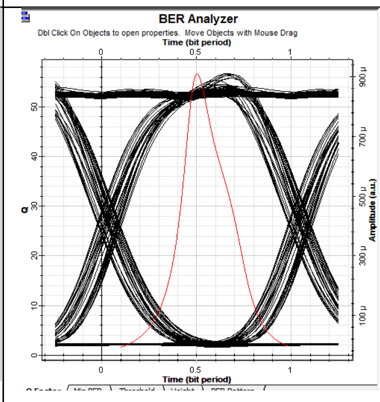
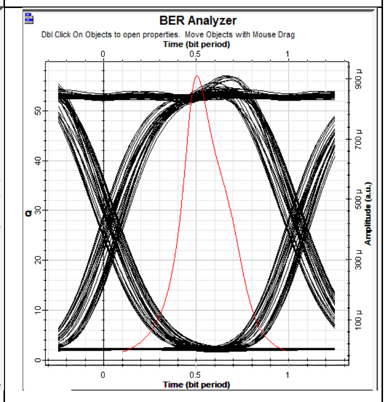
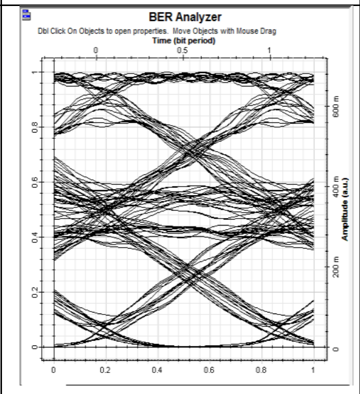
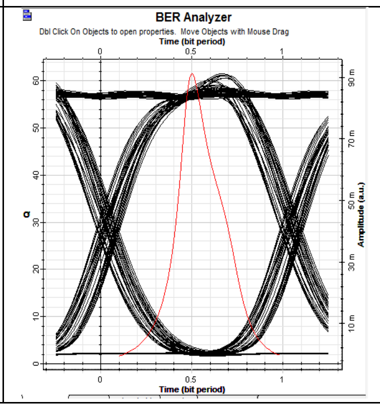
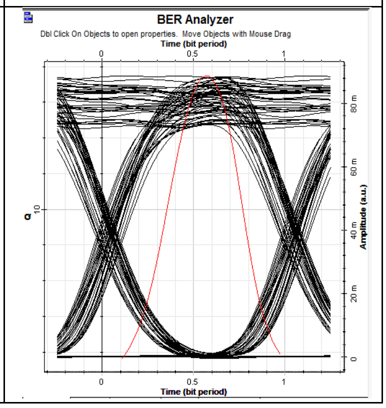
	30 Gbps		
	Without compensation	**Pre-compensation**	**Post-compensation**
-20 dBm			
0 dBm			
20 dBm			

Table 3.12 Eye diagram results obtained before and after using FBG at 60 Gbps.

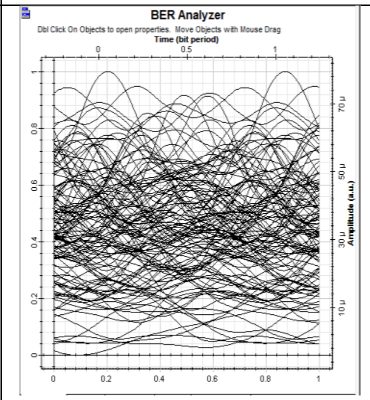
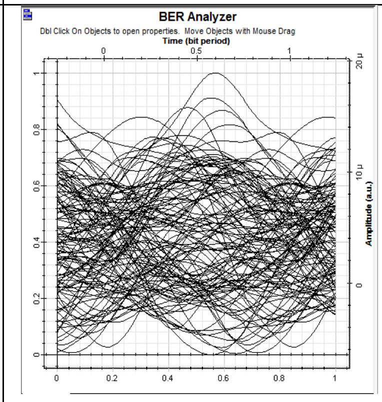
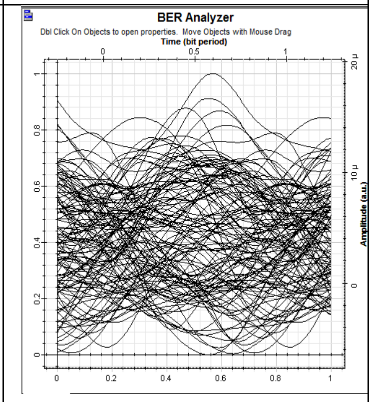
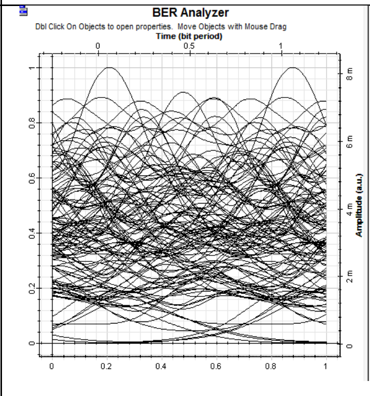
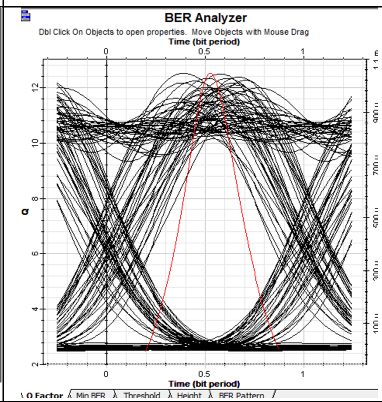
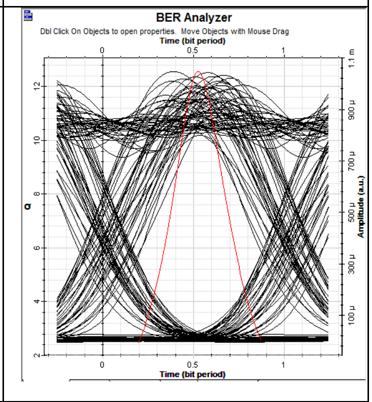
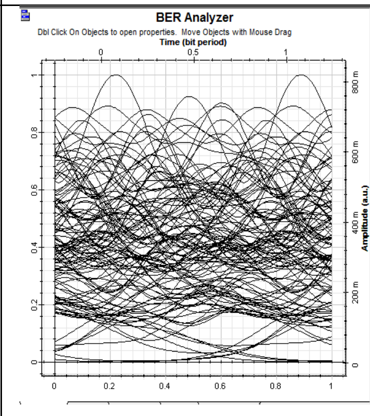
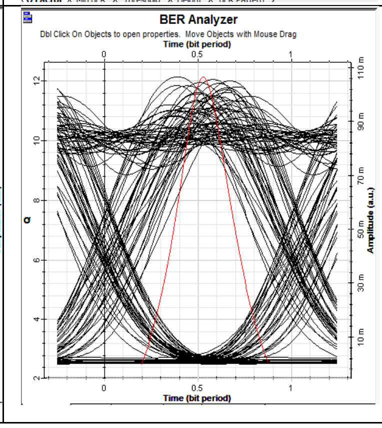
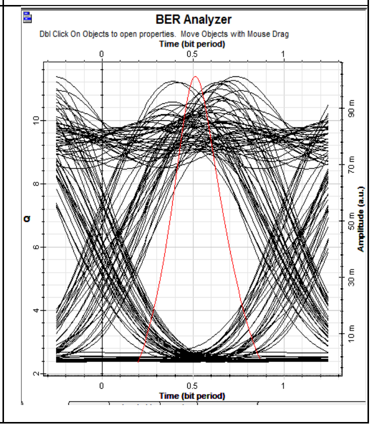
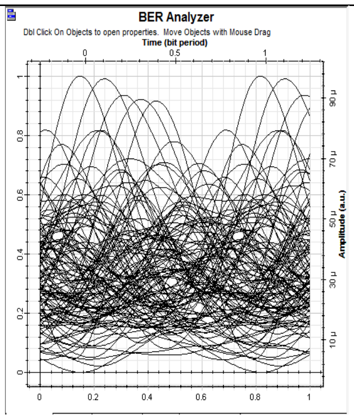
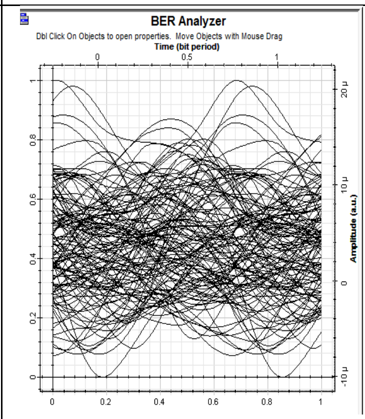
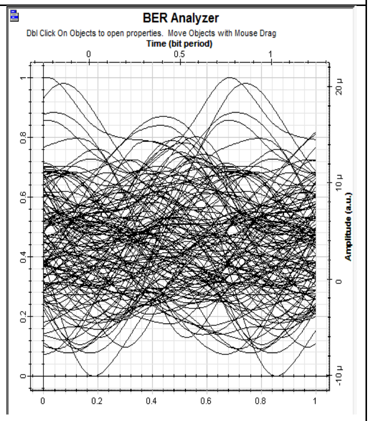
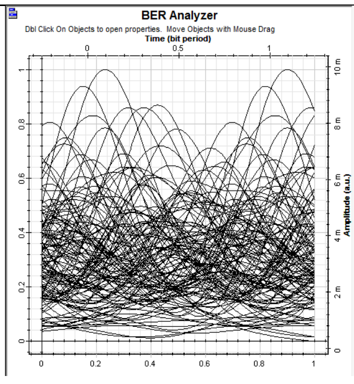
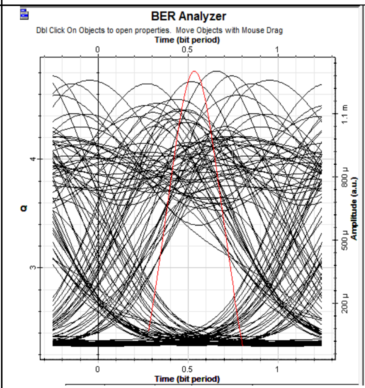
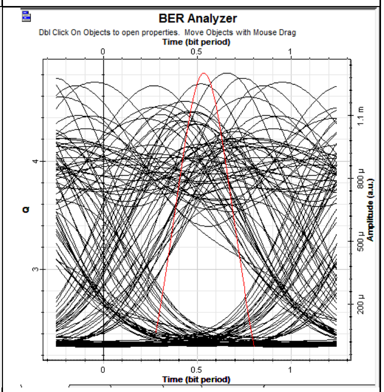
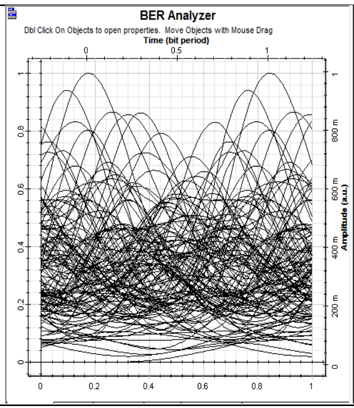
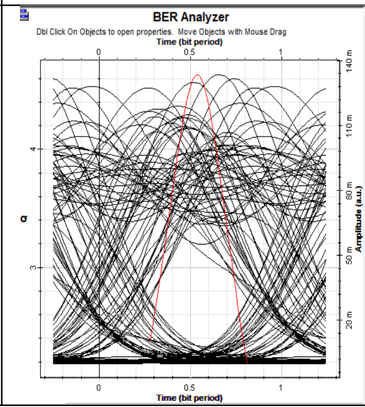
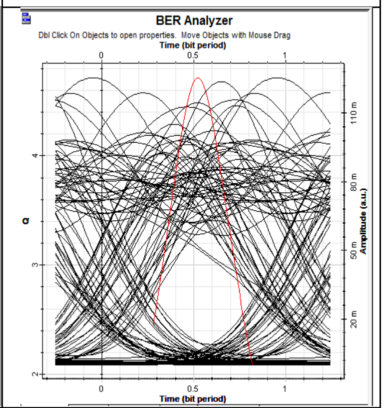
	60 Gbps		
	Without compensation	**Pre-compensation**	**Post-compensation**
-20 dBm			
0 dBm			
20 dBm			

Table 3.13 Eye diagram results obtained before and after using FBG at 90 Gbps.

	90 Gbps		
	Without compensation	**Pre-compensation**	**Post-compensation**
-20 dBm			
0 dBm			
20 dBm			

- **At 30 Gbps**

  From table 3.11, it is noticed that the system performance is bad for the conventional case for all input powers. Both FBG pre- and post-compensations result in a serious distortion at -20 dBm, whereas at 0 and 20 dBm they yield a wide open eye diagram. For 20 dBm, the eye diagram of pre-compensation is better than the one of the post.

- **At 60 Gbps**

  When no compensation technique is used, a sever distortion is seen for all input powers. Both pre- and post-compensations give a distortion at -20 dBm, while the system performance is enhanced at 0 and 20 dBm.

- **At 90 Gbps**

  It is seen from table 3.13 that there is a distortion of the signal for all input powers for the conventional case. Both FBG pre- and post-compensations result in a bad system performance at -20 dBm, whereas at both 0 and 20 dBm a small improvement is seen for both techniques.

3.4.7 General discussion

- When no compensation technique is used, the signal can not reach the receiver for all input powers due to the cumulative effect of dispersion, which causes the optical signals to be spread with inter-symbol interference.
- At low input powers, as the signal is very weak, it is easy to be absorbed by the waveguide material impurities or to escape out of the core even at smaller bending radius, so that it is easily attenuated. The use of FBG compensation technique did not improve the system performance as DCF technique did at this level of power.
- At high input powers, nonlinear effects become dominant; primarily SPM since it is proportional to the signal power transmitted. Using FBG at this power level provides the best compensation for the system compared to DCF.
- At high bit rates exceeding 90 Gbps, PMD affects the system severely causing a serious limitation by reducing the bandwidth. Thus either DCF or FBG compensation techniques do not increase the performance of the system at these data rates.
- At low bit rate and low input power, DCF compensation technique is more efficient.
- FBG is a cost effective choice compared to DCF technique because DCF introduces a more important degradation of the overall system performance which imposes the use of extra optical amplifiers.

3.5 Conclusion

In this chapter, the eight channel DWDM system point-to-point topology at 30, 60 and 90 Gbps for the conventional case and the two different compensation methods DCF and FBG was analyzed. A comparison in terms of BER and Q factor was undertaken. It is found that dispersion compensation is necessary to reduce losses and cost of the system. DCF techniques increase the total losses and the cost of optical transmission system due to non linear effects while FBG helps in decreasing the cost of the system but have a limited range.

4.1 Introduction

In today's world, the demand for optical networks is growing faster and faster. Networks are becoming bigger, more powerful and more reliable. This requires more operators, installers and maintenance contractors to provide information on networks faster and with higher accuracy than ever before.

4.2 OTDR definition

An optical time domain reflectometer (OTDR) is a fiber optic tester for the characterization of fiber and optical networks. The purpose of an OTDR is to detect, locate and measure events (splices, connectors, fiber breaks) at any location on a fiber link.

One of the main benefits of an OTDR is that it operates as one directional radar system, allowing for complete fiber characterization from only one end of the fiber. The OTDR generates geographical information of the resulting length versus the returned signal level on the display screen called a trace. The trace is a visual representation of the backscattering coefficient created by the OTDR to determine the events on the fiber optic link such as breaks, splice loss, bends, attenuation and distance [8].

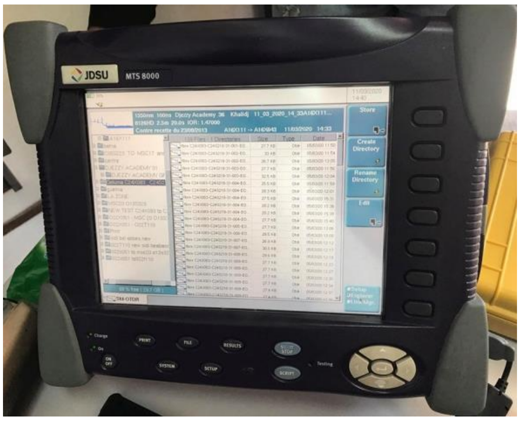


Figure 4.1 OTDR type JDSU MTS 8000.

4.3 Working principle of OTDR technology

The ability of the OTDR to characterize a fiber is based on detecting small signals that are returned back to it in response to the injection of a large signal, a process similar to radar technology. In this regard, the OTDR depends on two types of optical phenomena: Rayleigh scattering and Fresnel reflections.

When injecting a pulse of light into the fiber, some of the photons of light scatter in random directions due to microscopic particles, an effect referred as Rayleigh scattering. This effect provides amplitude and temporal information along the length of the fiber. In addition, some of the light is scattered back in the opposite direction of the pulse, which is referred to as the backscattered signal.

Rayleigh backscattering is used to calculate the level of attenuation in the fiber as a function of distance (expressed in dB/km), which is shown by a straight slope in an OTDR trace. Higher wavelengths are less attenuated than shorter ones and, therefore, require less power to travel over the same distance in a standard fiber.

The second type of reflection used by an OTDR is Fresnel reflection which detects physical events along the link. When the light hits an abrupt change in the refraction index (e.g., from glass to air) a higher amount of light is reflected back, creating Fresnel reflection, which can be thousands of times bigger than the Rayleigh backscattering. Fresnel reflection is identifiable by the spikes in an OTDR trace. Examples of such reflections are connectors, mechanical splices, bulkheads, fiber breaks or opened connectors.

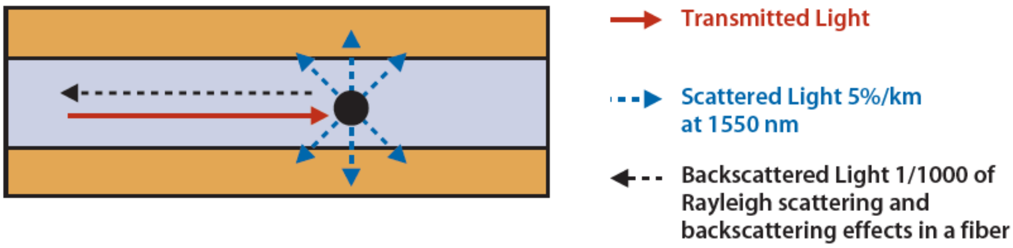


Figure 4.2 Rayleigh scattering and backscattering effects in a fiber [8].

In order to measure fiber attenuation, a fairly long length of fiber is needed with no distortions on either end from the OTDR. If the fiber looks nonlinear at either end, especially near a reflective event like a connector, that section should be avoided when measuring loss.

Connectors and splices are called "events" in OTDR. Both should show a loss, but connectors and mechanical splices will also show a reflective peak so they can be distinguished from fusion splices. Also, the height of that peak will indicate the amount of reflection at the event, unless it is so large that it saturates the OTDR receiver. Then, the peak will have a flat top and tail on the far end, indicating the receiver was overloaded. The width of the peak shows the distance resolution of the OTDR, or how close it can detect events.

OTDRs can also detect problems in the cable caused during installation. If a fiber is broken, it will show up as the end of the fiber much shorter than the cable. If excessive stress is applied on the cable due to kinking or too tight a bend radius, it will look like a splice at the wrong location [8]. Figure 4.3 represents the different events that an OTDR can detect.

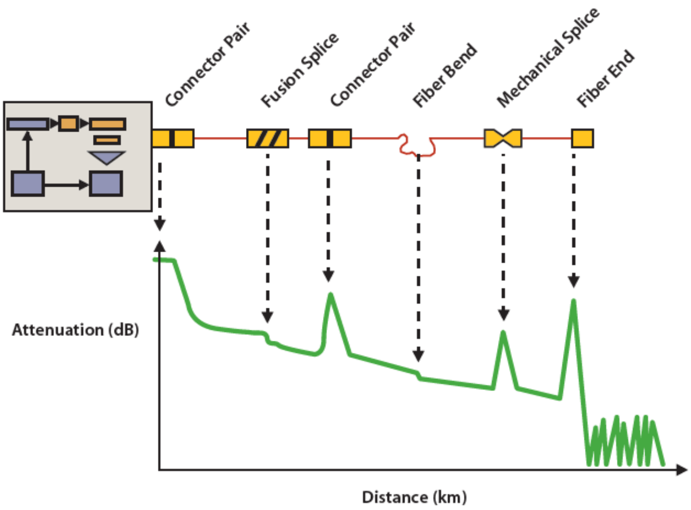


Figure 4.3 A typical OTDR trace [8].

4.4 OTDR measurements

The successful use of an OTDR requires knowing how to operate the instrument, choosing the proper measurement parameters and correctly interpreting the traces.

4.4.1 Event interpretation

a. Reflective event

When some of the pulse energy is scattered, reflective events happen. They occur at breaks, connector junctions, mechanical splices, or the indeterminate end of fiber. A reflective event is shown as a peak on the trace [35].

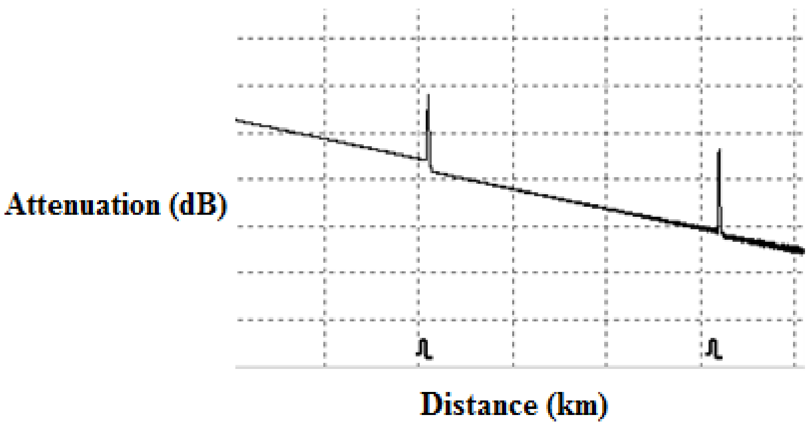


Figure 4.4 Reflective event [35].

b. Non reflective event

Non reflective events happen at certain points where there is some optical loss but no light scattering. They are generally produced by fusion splices or bending losses, such as macro bends. When a non reflective event occurs, a power decline shows on trace [35].

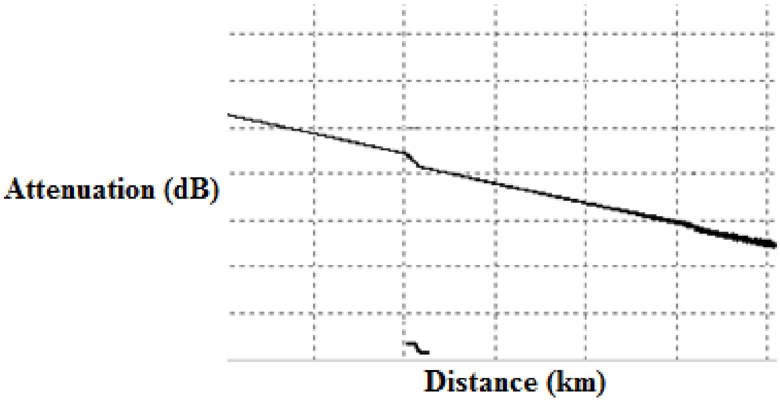


Figure 4.5 Non reflective event [35].

4.4.2 Reflectance

It represents the ratio of the reflected power to the incident power at a discrete location on the fiber span. Reflectance is expressed in decibels (dB). A small negative value indicates a higher reflection than a large negative value. A larger reflectance will appear as a higher peak on the trace waveform [8].

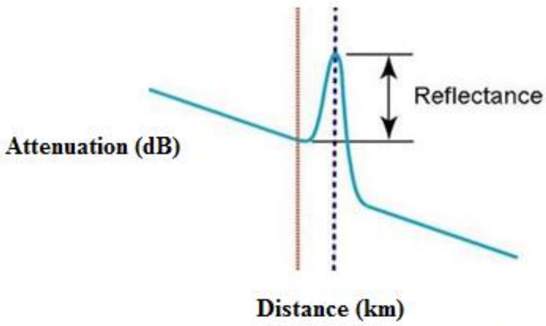


Figure 4.6 Reflectance [36].

4.4.3 Optical return loss (ORL)

Optical return loss (ORL) is the inverse of reflectance, and has an opposite sign. However, the term has been adopted by OTDR manufacturers to mean something different; the total of all reflectance events and total fiber backscatter over the entire length of fiber being tested [8].

4.4.4 Measurement contents of OTDR

An OTDR can perform the following measurements [8]:

- For each event: Distance location, loss, and reflectance.

- For each section of fiber: Section length, section loss (in dB), section loss rate (in dB/km), and optical return loss (ORL) of the section.
- For the complete terminated system: Link length, total link loss (in dB), and ORL of the link.

4.4.5 Measurement methods

The OTDR allows technicians to perform measurements on the fiber span in different ways: full automatic and manual [8].

a. Full automatic method

Most modern OTDRs perform fully automatic measurements with one input from technicians, by auto detecting and measuring all of the events, sections and fiber ends, using an internal detection algorithm. Figure 4.7 represents the automatic event detection.

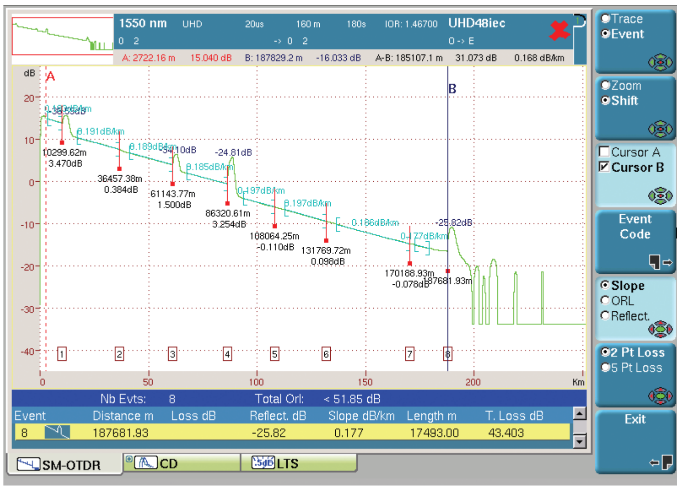


Figure 4.7 Automatic event detection [7].

b. Manual method

Experienced technicians usually do not use the auto-configuration feature altogether and enter the acquisition parameters based on experience and knowledge of the link under test. The setting items include:

❖ **Refraction index**

Refraction index is the calibration for the speed of light in the fiber which the OTDR uses to calculate distance in the fiber. If using the refractive index reported by the fiber manufacturer, the OTDR will report the fiber length accurately. However, particularly during fault location, technicians want to determine the cable length instead of fiber length. For this reason, it is often recommended to measure a known length of similarly constructed cable and determine the effective refractive index that will allow the OTDR to report cable length instead of fiber length.

- **Wavelength**

The user can select the option of testing the fiber at one or two wavelengths. For example, single mode fiber is tested at 1310 and/or 1550 nm. However, 1550 nm is more sensitive to bends in the fiber than 1310 nm, whereas 1310 nm will generally measure splice and connector losses higher than 1550 nm.

- **Pulse width**

The duration of the OTDR pulse width controls the amount of light that is injected into a fiber. The more light energy injected, the greater the backscattered signal.

Long pulses yield traces with less noise and longer distance capability with a lower ability to resolve and identify events, whereas short pulses allow the OTDR to reach the end of the cable plant with a reasonable number of averages providing a good resolution.

- **Range**

The range of an OTDR is defined as the maximum distance from which the OTDR can acquire data samples. The longer the range, the further the OTDR will shoot pulses down the fiber. The range is generally set at twice the distance to the end of the fiber. If the range is set incorrectly, the trace waveform may contain measurement artifacts, such as ghosts.

- **Averaging**

Averaging is the process by which each acquisition point is sampled repeatedly, and the results are averaged in order to improve the signal-to-noise ratio (SNR).

Increasing the number of averages results in a cleaner trace. For example, an acquisition using 3 minute averaging will improve the dynamic range by 1.2 dB when compared to an acquisition using 1 minute averaging.

4.5 OTDR experimental results

The optical system simulated previously in chapter three; figure 3.1, will be studied and discussed in a real setting.

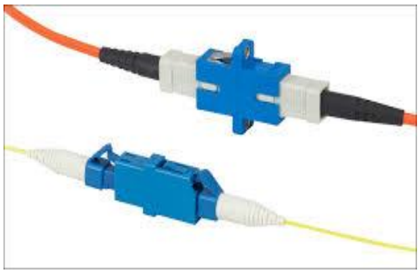
4.5.1 The objective

The objective of this test is to understand the working principle of an OTDR and to take real time measurements of a single mode fiber.

4.5.2 Equipment needed to perform the test

- G.652.D cable of 0.696 km length.
- JDSU MTS 8000 OTDR with the following specifications:
  - Dynamic range: 45 dB at calibrated wavelengths (850, 1310, 1490, 1550, 1625 and 1650 nm), -45 dBm from 800 to 1250 nm.
  - Wavelength range: 800 to 1650 nm.
  - Event dead zone: 1 m.
  - Attenuation dead zone: 8 m.
  - Display resolution: 0.001 dB.
  - Accuracy: ± 0.05 dB.
- Launch fiber ring cable of 2 km length.
- Connectors of type FC/PC.
- Mating adapters compatible to connectors.
- Cleaning supply.

(a)



(b)

(c)

Figure 4.8 Equipment needed for the OTDR test

(a) Fiber ring cable (b) Mating adapters (c) Cleaning supply.

4.5.3 Testing procedure

The measurements have been done between the two sites **A16X111 Djezzy Academy** and **A16M471 El Mouradia**, where the blue cable consisting of 12 fibers and relating the two sites is the one under test.

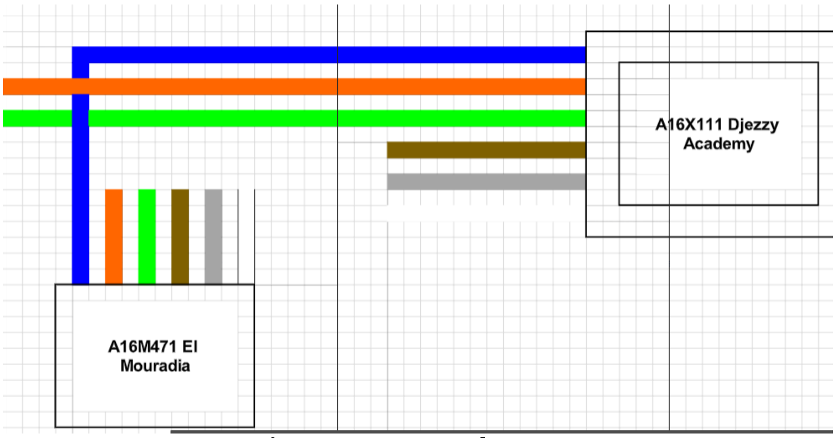


Figure 4.9 Site schematic.

The 12 fibers have been tested at both of 1310 and 1550 nm following the steps below:

- Turning on the OTDR and allowing time to warm-up.
- Cleaning all connectors and mating adapters.
- The launch cable should be attached to the OTDR.
- Attaching the cable to test to the end of the launch cable.
- Choosing the method of measurement, in this case the full automatic method has been used.
- Acquiring the trace.

The experimental setup is as follows:

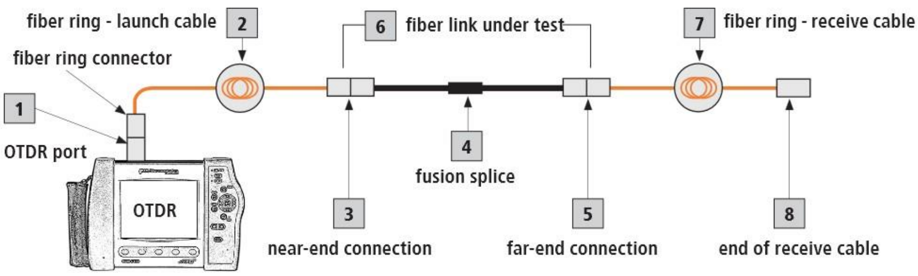


Figure 4.10 The experimental setup used to perform the experiment.

Remarks

- The fiber ring-receive cable has not been used in the tests but it can be used in other cases.

- In the full automatic method, the only thing the user needs to select is the wavelength (1310 or 1550 nm), all the other parameters are determined by the OTDR. Those parameters are:
  - The index of refraction: 1.47.
  - The pulse width: 30 ns.
  - The range: 5 km.
  - Averaging time: 10 s.
- An OTDR launch fiber, often available on a small spool or within a “launch box”, provides both the time and distance required for the OTDR to effectively look at and measure the characteristics of the entire length of the fiber being tested, especially the length closest to the OTDR.

4.5.4 Observations

The traces of fiber number one at both wavelengths are shown in figures 4.11 and 4.12.

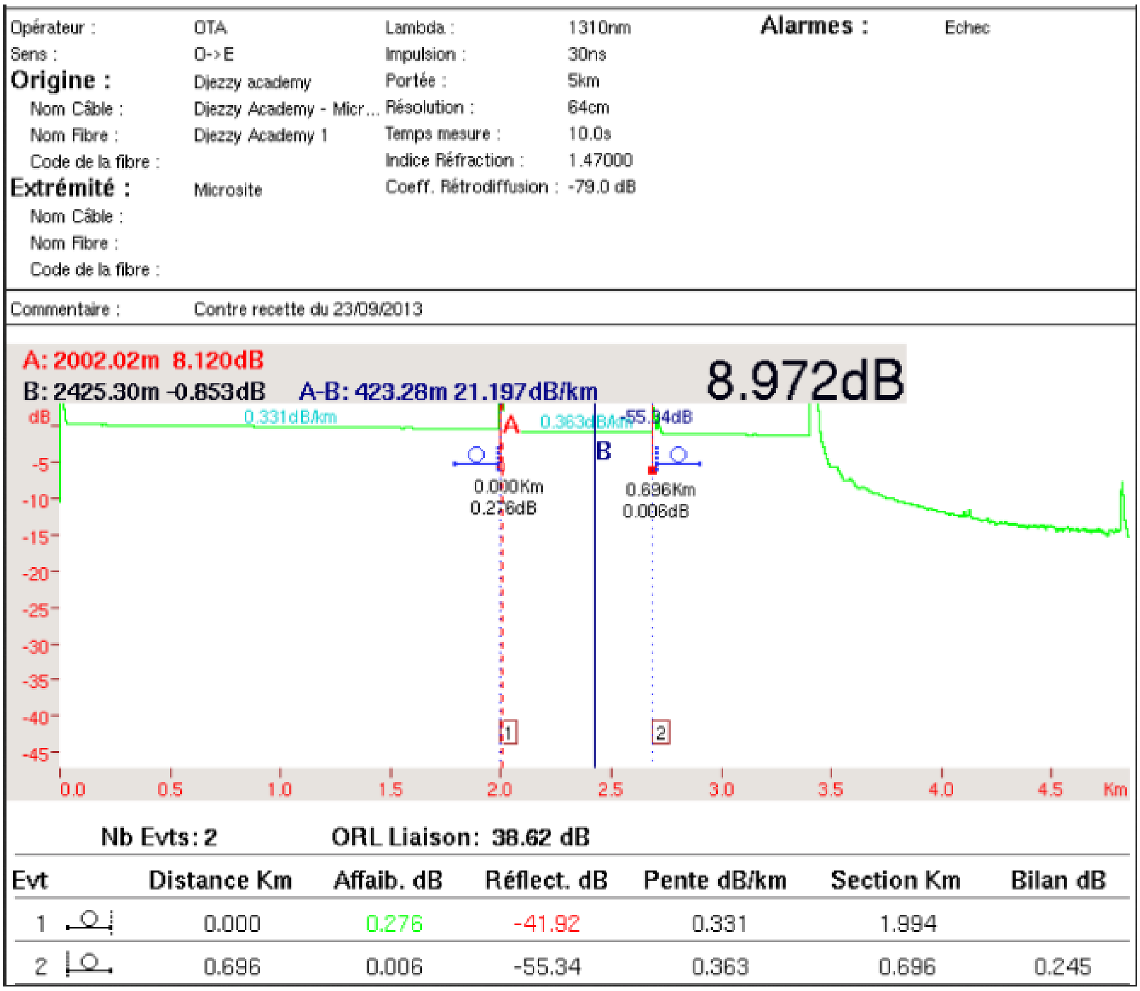


Figure 4.11 Characteristics of the link Djezzy Academy – El-Mouradia at 1310 nm.

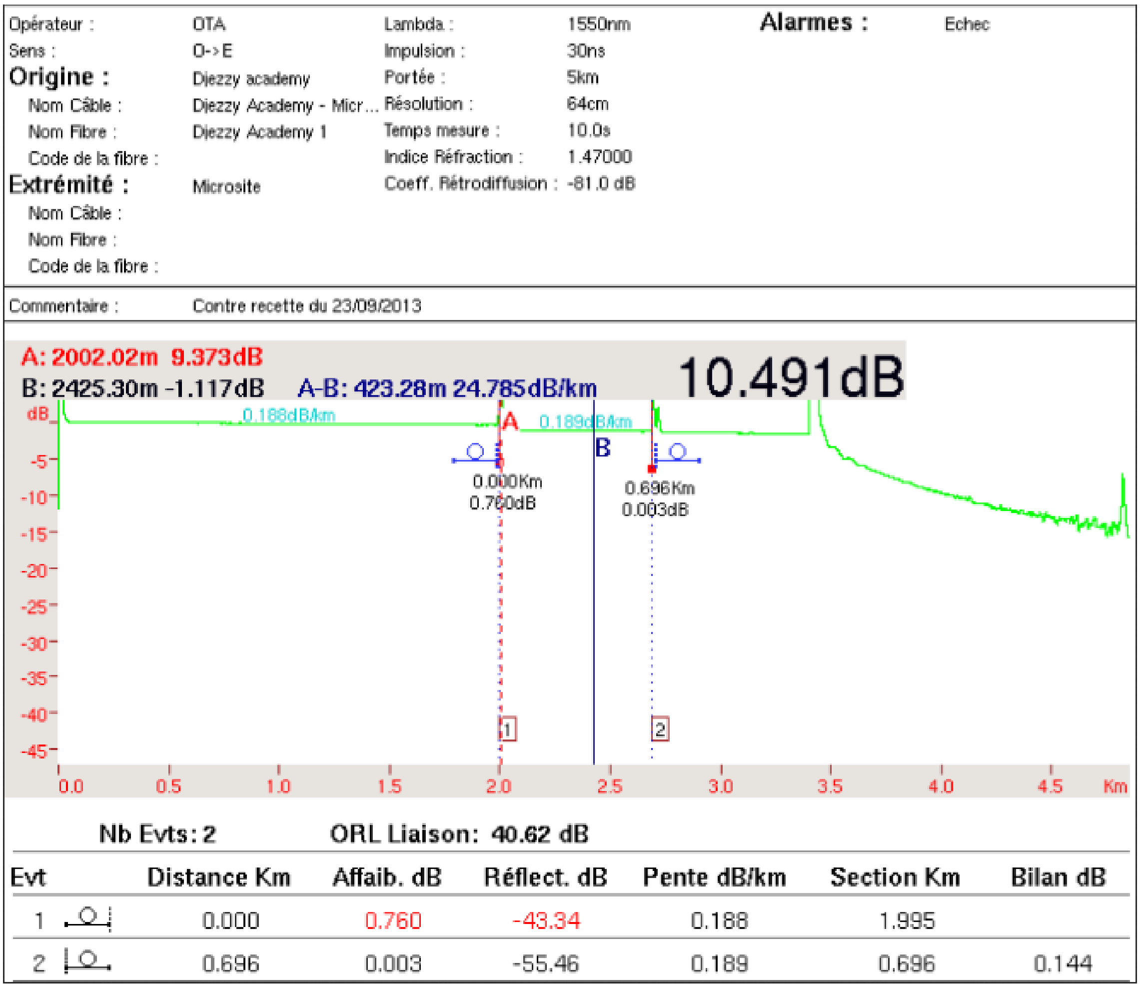


Figure 4.12 Characteristics of the link Djezzy Academy – El-Mouradia at 1550 nm.

4.5.5 Trace analysis

The traces represent the attenuation of fiber 1 in dB versus the distance in km at two wavelengths 1310 and 1550 nm.

The two graphs show a peak at first which is called the “dead zone” that can cause improper readings that’s why the fiber launch cable is used to eliminate it. The cable is shown as a straight line on the trace with a length of 2 km.

At point 1 which is about 2 km far from the origin, a reflective event can be seen which indicates the presence of the first connector. This type of events results from Fresnel reflection. The attenuation of this event is:

- 0.276 dB at 1310 nm with a reflectance of -41.92 dB.
- 0.76 dB at 1550 nm with a reflectance of -43.34 dB.

From 2 km to 2.696 km, the pulsation has reached the section needed to be tested between point 1 and point 2 which makes a link of 0.696 km with a total attenuation of 0.245 dB at 1310 nm and 0.144 dB at 1550 nm.

At point 2 which is about 2.696 km, the second reflective event can be seen clearly and it represents the second connector with an attenuation of:

- 0.006 dB and a reflectance of -55.34 dB.
- 0.003 dB and a reflectance of -55.46 dB.

After 2.696 km, only noise appears because there is no fiber ring-receive cable attached to the fiber.

Remarks

- As indicated in the system layout in figure 3.5, there exist three splices. However, they are not clearly shown on the trace. The two splices at the extremity did not appear due to the effect of the wide pulse width used 30 ns causing the inability of OTDR to display neighboring events separately, whereas the good fabrication of the middle fusion splice made the OTDR unable to detect it.
- Shorter cable lengths require shorter pulse width, since this will maximize the resolution, while minimizing energy output. Short pulse width is especially useful for evaluating segments of cable that are closer to the OTDR. Since it will produce shorter dead zones, hence a greater ability to detect events that are closely spaced.

4.5.6 Experimental results

The tables below represent the results obtained after testing the 12 fibers.

Table 4.1 Event table of fiber 1.

Wavelength (nm)	Event number	Distance (km)	Attenuation (dB)	Reflectance (dB)	Attenuation coefficient (dB/km)	Section (km)	Accumulation (dB)
1310	1	0	0.276	-41.92	0.331	1.994	
	2	0.696	0.006	-55.34	0.363	0.696	0.245
1550	1	0	0.76	-43.34	0.188	1.995	
	2	0.696	0.003	-55.46	0.189	0.696	0.144

Table 4.2 Event table of fiber 2.

Wavelength (nm)	Event number	Distance (km)	Attenuation (dB)	Reflectance (dB)	Attenuation Coefficient (dB/km)	Section (km)	Accumulation (dB)
1310	1	0	0.635	-54.4	0.331	1.995	
	2	0.695	0.5	-28.86	0.347	0.695	0.241
1550	1	0	0.767	-47.80	0.179	1.995	
	2	0.695	1.995	>-7.38	0.227	0.695	0.159

Table 4.3 Event table of fiber 3.

Wavelength (nm)	Event number	Distance (km)	Attenuation (dB)	Reflectance (dB)	Attenuation Coefficient (dB/km)	Section (km)	Accumulation (dB)
1310	1	0	0.388	-45.82	0.331	1.994	
	2	0.695	0.657	>-9.15	0.355	0.695	0.247
1550	1	0	0.594	-51.63	0.186	1.995	
	2	0.695	0.622	>-7.63	0.195	0.695	0.137

Table 4.4 Event table of fiber 4.

Wavelength (nm)	Event number	Distance (km)	Attenuation (dB)	Reflectance (dB)	Attenuation Coefficient (dB/km)	Section (km)	Accumulation (dB)
1310	1	0	0.340	>-19.31	0.331	1.993	
	2	0.697	0.004	-54.51	0.345	0.697	0.243
1550	1	0	0.781	-24.75	0.185	1.994	
	2	0.696	0.001	-54.41	0.252	0.696	0.160

Table 4.5 Event table of fiber 5.

Wavelength (nm)	Event number	Distance (km)	Attenuation (dB)	Reflectance (dB)	Attenuation Coefficient (dB/km)	Section (km)	Accumulation (dB)
1310	1	0	0.310	-58.62	0.331	1.995	
	2	0.695	-0.673	-60.31	0.334	0.695	0.231
1550	1	0	0.629	-59.62	0.184	1.995	
	2	0.696	-0.691	-61.78	0.209	0.696	0.146

Table 4.6 Event table of fiber 6.

Wavelength (nm)	Event number	Distance (km)	Attenuation (dB)	Reflectance (dB)	Attenuation Coefficient (dB/km)	Section (km)	Accumulation (dB)
1310	1	0.000	0.907	-53.54	0.330	1.994	
	2	0.694	0.006	-33.03	0.341	0.694	0.244
1550	1	0.000	1.155	-54.58	0.181	1.995	
	2	0.694	0.003	-33.36	0.188	0.694	0.138

Table 4.7 Event table of fiber 7.

Wavelength (nm)	Event number	Distance (km)	Attenuation (dB)	Reflectance (dB)	Attenuation Coefficient (dB/km)	Section (km)	Accumulation (dB)
1310	1	0.000	0.453	-54.22	0.330	1.994	
	2	0.695	0.006	-52.16	0.514	0.695	0.276
1550	1	0.000	0.900	-55.46	0.186	1.995	
	2	0.695	0.001	-52.70	0.207	0.695	0.173

Table 4.8 Event table of fiber 8.

Wavelength (nm)	Event number	Distance (km)	Attenuation (dB)	Reflectance (dB)	Attenuation Coefficient (dB/km)	Section (km)	Accumulation (dB)
1310	1	0.000	0.176	-33.85	0.328	1.994	
	2	0.695	0.006	-49.62	0.432	0.695	0.365
1550	1	0.000	0.634	-35.38	0.185	1.994	
	2	0.696	0.003	-50.22	0.244	0.696	0.210

Table 4.9 Event table of fiber 9.

Wavelength (nm)	Event number	Distance (km)	Attenuation (dB)	Reflectance (dB)	Attenuation Coefficient (dB/km)	Section (km)	Accumulation (dB)
1310	1	0.000	0.287	-54.97	0.328	1.994	
	2	0.695	0.075	-51.40	0.339	0.695	0.240
1550	1	0.000	0.675	-56.11	0.181	1.995	
	2	0.695	0.001	-52.02	0.189	0.695	0.151

Table 4.10 Event table of fiber 10.

Wavelength (nm)	Event number	Distance (km)	Attenuation (dB)	Reflectance (dB)	Attenuation Coefficient (dB/km)	Section (km)	Accumulation (dB)
1310	1	0.000	0.723	-54.56	0.332	1.994	
	2	0.695	0.006	-50.57	0.329	0.695	0.225
1550	1	0.000	0.992	-55.77	0.181	1.995	
	2	0.695	0.001	-51.33	0.220	0.695	0.166

Table 4.11 Event table of fiber 11.

Wavelength (nm)	Event number	Distance (km)	Attenuation (dB)	Reflectance (dB)	Attenuation Coefficient (dB/km)	Section (km)	Accumulation (dB)
1310	1	0.000	0.347	-31.48	0.331	1.994	
	2	0.695	0.006	-46.73	0.345	0.695	0.266
1550	1	0.000	0.697	-32.79	0.184	1.994	
	2	0.696	0.003	-47.72	0.242	0.696	0.175

Table 4.12 Event table of fiber 12.

Wavelength (nm)	Event number	Distance (km)	Attenuation (dB)	Reflectance (dB)	Attenuation Coefficient (dB/km)	Section (km)	Accumualtion (dB)
1310	1	0.000	0.266	-63.95	0.331	1.995	
	2	0.694	0.006	-43.00	0.332	0.694	0.229
1550	1	0.000	0.711	-64.20	0.185	1.995	
	2	0.694	0.003	-44.03	0.130	0.694	0.091

The table below summarizes the total attenuation in the 12 fibers at both 1310 and 1550 nm wavelengths.

Table 4.13 System performance comparison.

Fiber number	Total attenuation at 1310 nm	Total attenuation at 1550 nm
1	0.245	0.144
2	0.241	0.159
3	0.247	0.137
4	0.243	0.160
5	0.231	0.146
6	0.244	0.138
7	0.276	0.173
8	0.365	0.210
9	0.240	0.151
10	0.225	0.166
11	0.266	0.175
12	0.229	0.091

4.5.7 Discussion

To decide whether the results are good or not, a comparison must be done between these measurements and the theoretical value of the total attenuation in dB.

The total attenuation is the sum of the losses of the different elements in the channel including fiber loss, splicing loss and the patch connector loss, it is given by:

$$A = \sum_{i=1}^{N} A_i + \sum_{j=1}^{M} A_j + \alpha_L L \tag{4-1}$$

Where:

A: total attenuation in dB.

A_i : loss of splice in dB.

A_j : loss of connector in dB.

α_L : attenuation coefficient in dB/km.

L: length of the cable in km.

N: number of splices.

M: number of connectors.

Splice and connector losses are taken respectively as: 0.1 dB and 0.3 dB.

At 1310 nm:

$$A = 0.1 \times 3 + 2 \times 0.3 + 0.36 \times 0.696$$

$$\boldsymbol{A = 1.15\ dB}$$

At 1550 nm:

$$A = 0.1 \times 3 + 2 \times 0.3 + 0.22 \times 0.696$$

$$\boldsymbol{A = 1.05\ dB}$$

- Since the measurements in table 4.13 are less than the theoretical value of the total attenuation at both wavelengths, the results are good and need not to be repeated.
- The OTDR results reveal that the loss at 1550 nm is less than the one at 1310 nm. This is due mainly to the wavelength sensitivity: 1310 nm is more sensitive to alignment problems whereas 1550 nm is more sensitive to fiber bending problems.

Remarks

- Testing at both wavelengths 1310 and 1550 nm is important, because in modern DWDM systems both are used at the same time: 1310 nm is used for transmission whereas 1550 nm for reception.
- Losses are minimized when testing at 1550 nm that means a better signal-to-noise ratio and dynamic range, hence a higher quality signal.

4.6 Conclusion

The reliability and quality of an OTDR is based on its accuracy, measurement range, measurement speed, ability to measure closely spaced events and operate satisfactorily under various environmental and physical abuses. The instrument is also judged on the basis of its cost, provided features, size and ease of use.

OTDR has been and will continue to be a valuable and powerful tool for performing many measurements on optical cables. The accuracy limitation of OTDR for both distance and loss measurements are quantifiable and allow the user to maximize the effectiveness of this instrument.

Conclusion

In this project, the performance of an optical communication system has been analyzed by using DCF and FBG. The analysis was conducted on the basis of results obtained from Optisystem simulation tool, various parameters were used i.e. input power and input bit rate. In both schemes (pre and post) FBG based system, if the input power increases, it induces a decrease in BER. On the other hand, increasing the input bit rate reduces the quality factor of FBG based system. On comparing the two schemes it was found that the pre FBG gives optimum results. Similarly, in these schemes of DCF based system, it was found that as the input bit rate increases; it reduces the quality factor of the system whereas a decrease in BER is observed when increasing the input power. On comparing both the systems; one with DCF and other with FBG it can be concluded that FBG results in better system performance but has a limited range. Last, OTDR has been used to verify splice loss, measure length and locate fiber faults and defects. As a result, we can say that due to widely using optical fibers, it is very important to select a suitable technique to quickly detect occurring faults with the minimum cost.

For a reliable communication over long distances, it is necessary to reduce the effect of both dispersion and attenuation by choosing an appropriate dispersion compensation technique as well as an accurate measurement tool.

Future Work

- In the future, symmetrical compensation scheme can be used to enhance the effect of dispersion in the optical fiber system.
- Highly efficient amplifiers can be used to strengthen the signal while transmitting through the optical fiber cable.
- Material chosen should have optimum refractive index to support efficient transmission with minimum loss.
- Consider compensation techniques beyond 1 km length of fiber.
- DCF is among the most technological challenges facing developers of 90 Gbit/s systems due to the nature of PMD that makes it the most difficult challenge.
- A receive launch cable can be placed at the fiber end to avoid noise; making the link end looks as a straight line in the OTDR trace.
- Short pulses can be used to detect closely spaced events.

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Appendix A

1. Data source

Generally defined as the initial location where data is created or where physical information is first digitized. At the transmitter data source, two types of sequences are generated:

1.1 Pseudo random bit sequence (PRBS)

It is a binary sequence generated with a deterministic algorithm. However, it is difficult to predict and exhibits statistical behavior similar to a truly random sequence.

1.2 User defined bit sequence

Unlike PRBS that generates random pulses at the output, the user defined bit sequence gives a specific output based on a particular bit sequence given by the user.

2. Pulse generator

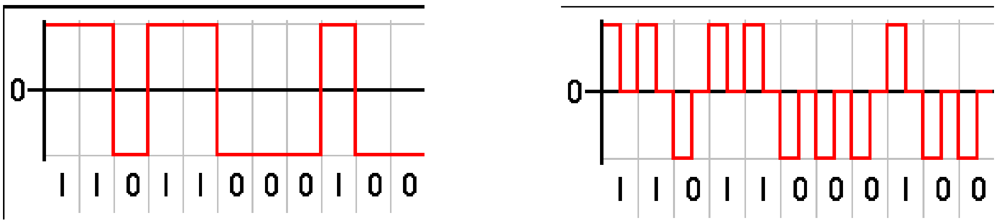
Various coding methods are used to transmit signals over a communication system. In optical communication, two types of coding exist: The Return-to-Zero (RZ) and Non-Return-to-Zero (NRZ).

2.1 The Return-to-Zero format

It demonstrates a line code where the signal returns to zero between each pulse, in addition of being self clocking which means that no need to send different clocks alongside the signal. But, it has a big bandwidth because of the time taken during ON OFF transitions.

2.2 The Non-Return-to-Zero format

It describes a line code where ones are represented usually by a positive voltage while zeros are represented by a negative voltage. The signal has a smaller bandwidth and a higher carried energy compared to RZ method. However, it is not inherently a self clocking indicator, so some other synchronization technique must be used for avoiding fragment slips.



(a) (b)

Figure A.1 Examples of coding formats in optical fiber communication

(a) NRZ format (b) RZ format

3. Optical sources

Among the variety of light sources, optical fiber communication systems almost always use semiconductor-based light sources such as light-emitting diodes (LEDs) and laser diodes because of the several advantages such sources have over the others. These advantages include compact size, high efficiency, required wavelength of emission, and above all, the possibility of direct modulation at high speeds.

3.1 Led diode

A LED is a junction diode made from semiconductor compound gallium arsenide phosphide. LEDs used as optical fiber transmitters emit infrared radiation at a wavelength of about 850 nm (0.85 µm).

Pulse code modulated signals from the coder supply input current to the LED. This will produce equivalent stream of infrared pulses for transmission along the optical fiber system. The spectral spread of wavelengths in the output is about 30-40 nm.

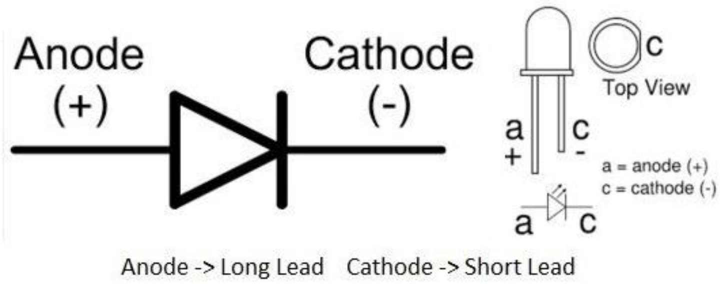


Figure A.2 A led diode

LEDs are very cheap and convenient source of light. They are usually used with multimode fibers due to their low output intensity. They are employed in low data rate digital transmission systems, up to speed of about 30 Mbps. Lens between LED and fiber system will improve light energy transmission between them.

3.2 Laser diode

Laser is derived from Light Amplification by the Stimulated Emission of Radiation. It produces a very intense beam of light which have the following properties.

- Monochromatic (meaning consists of one wavelength).
- Coherent (meaning all parts are in phase).
- Collimated (meaning all parts travel in one and same direction).

Laser diode used in optical fiber systems are made of gallium arsenide phosphide. The laser having size of a grain of sand can produce power output of about 10 mW.

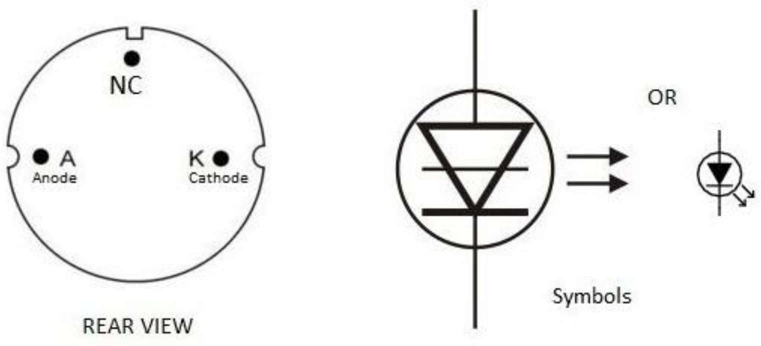


Figure A.3 A laser diode

ON/OFF switching speed of laser is faster than that of the LED. Spectral spreading is less than that of the LED about 1 to 2 nm or even less. Hence dispersion is not a problem with laser compared to LED. Hence lasers are suited for optical fiber systems used for single mode and high bit rate systems.

4. Optical modulator

Optical modulators are used in optical communication systems to convert electrical signals representing data or voice into modulated optical signals. Two strategies can be used to perform this operation: direct modulation and external modulation.

4.1 Direct modulation

In this modulation type, the output power of device depends directly on the input current. This means light is emitted from the device when "1 (binary one)" is being transmitted and no light is emitted when "0 (binary zero) " is being transmitted.

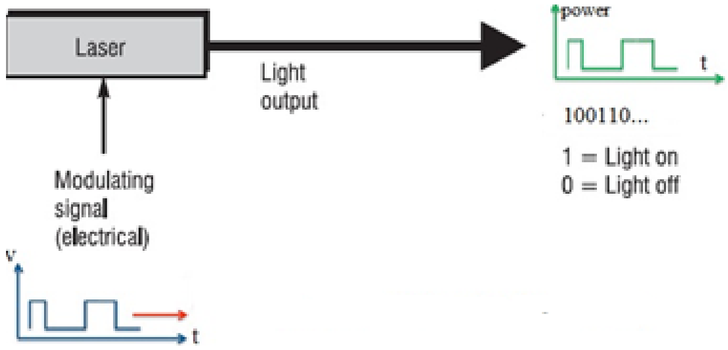


Figure A.4 Direct modulation of a laser

Both Laser and LED devices can be directly modulated using digital as well as analog signals.

- **Advantages**

- The optical modulation is simple.
- It is cheaper as no complex circuitry is involved during modulation process.

- **Disadvantages**

- This method is slower compared to indirect or external modulation type.

4.2 External modulation

In this method, external device is incorporated to modulate the intensity/phase of the light source. The light source is kept ON and external modulator is used which acts as switch/shutter. This switch is controlled by the information to be transmitted.

External modulation can be accomplished using an integrated optical modulator which uses a waveguide Mach-Zehnder interferometer. External modulation can also be accomplished using electro-optic modulation, magneto-optic modulation and acoustic-optic modulation processes.

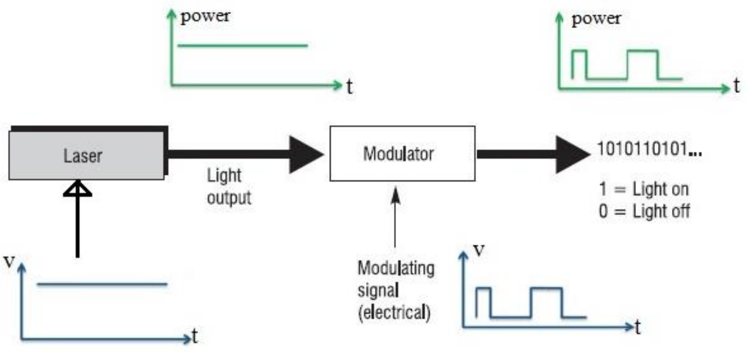


Figure A.5 External modulation of a laser

- **Advantages**

- Provides fast processing.
- It can be used with high power laser devices.
- It can be employed in high speed applications e.g. long haul telecom or cable TV head ends.

- **Disadvantages**

- It is expensive.
- High frequency RF modulation circuit is required for operation which usually will be complex.

5. Photodiode

It is a semiconductor device that converts light into electrical current or voltage based on its mode of operation. It comprises optical filters, built in lenses and surface areas. A photodiode has a slow response time as its surface area increases. Several types are available but the ones used in the optical receiver are: the PIN photodiode and the Avalanche Photodiode (APD).

5.1 PIN photodiode

In order to operate at longer wavelengths where the light penetrates more deeply into the semiconductor material, a wider depletion region is necessary. To achieve this, the n-type material is doped so lightly, and to make a low-resistance contact a highly doped n-type (n+) layer is added. This creates a PIN structure, as may be seen in figure A.6 where all the absorption takes place in the depletion region.

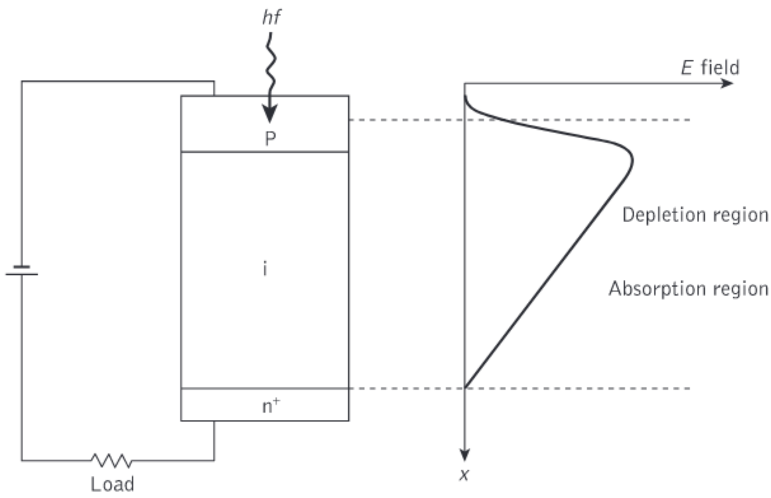


Figure A.6 The PIN photodiode showing the combined absorption and depletion regions

A photodiode operates in the reverse bias which will keep the depletion layer free of any carriers and normally no current will flow. However, when a light photon enters the intrinsic region it can strike an atom in the crystal lattice and dislodge an electron. In this way a hole electron pair is generated. The hole and electron will then migrate in opposite directions under the action of the electric field across the intrinsic region and a small current can be seen to flow.

The size of the current is proportional to the amount of light entering the intrinsic region. The more light, the greater the numbers of hole electron pairs that are generated and the greater the current flowing. This mode of operation is known as the photoconductive mode.

A photodiode can operate also under zero bias conditions when no external reverse potential is provided to the device. Light falling on the diode causes a current across the device, leading to forward bias which in turn induces “dark current” in the opposite direction to the photocurrent. This is called the photovoltaic mode, and it is the basis for solar cells.

5.2 Avalanche Photodiode (APD)

The avalanche photodiode possesses a similar structure to that of the PN or PIN photodiode. An avalanche diode structure similar to that of a Schottky photodiode may also be used but the use of this version is much less common. The main difference between the avalanche photodiode and other forms of photodiode is that it operates under a high reverse bias condition. This enables avalanche multiplication of the holes and electrons created by the photon /light impact.

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. Their velocity will increase in such a manner that when they collide with the lattice, they will create further hole-electron pairs and the process will repeat. The avalanche action enables the gain of the diode to be increased many times, providing a very much greater level of sensitivity.

1. Basic types of multiplexing

Multiplexing is the process of combining multiple signals into one signal, over a shared medium. It can be applied to both analog and digital signals. A benefit of using multiplexing, is reducing the physical hardware cost for expensive dedicated network communication segments, like fiber cables. Basic types of multiplexing that are widely utilized by telephone and data service providers include TDM, CDM, FDM and WDM.

1.1 Time Division Multiplexing (TDM)

Time division multiplexing is a digital technology which uses time, instead of space or frequency, to separate the different data streams. At the transmit side, each signal is allotted a time slot periodically, in a sequence, on a round-robin basis which allow the devices to send in turn. The multiple time slots constitute a frame and synchronization bits are inserted to identify the "Start' and Stop" of the frame.

The TDM at the receive side, known as the demultiplexer, separates the incoming composite signal into parallel streams. Both multiplexer and demultiplexer are synchronized by a common clock to receive data in accordance with the transmit sequence. Figure B.1 illustrates the concept of TDM.

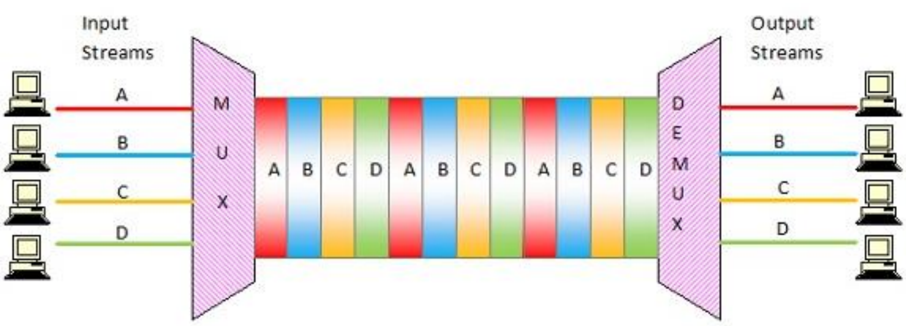


Figure B.1 Time division multiplexing technique

1.2 Code Division Multiplexing (CDM)

Code division multiplexing is a technique in which each channel transmits its bits as a coded channel specific sequence of pulses called chips. This coded transmission typically is accomplished by transmitting a unique time dependent series of short pulses, which are placed within chip times within the larger bit time. All channels, each with different code, can be transmitted on the same fiber and asynchronously demultiplexed. The specific version of

CDM used in cell phones is known as Code Division Multi-Access (CDMA) which optimizes the use of available bandwidth without interference between the users.

1.3 Frequency Division Multiplexing (FDM)

Frequency division multiplexing is a technique by which the total bandwidth is divided to a set of frequency bands that do not overlap. Each of these bands is a carrier of a different signal that is generated and modulated by one of the sending devices. The frequency bands are separated from one another by strips of unused frequencies called the guard bands, to prevent overlapping of signals.

The modulated signals are combined into a single signal that is transmitted over the communication channel, thus allowing multiple independent data streams to be transmitted simultaneously. At the receiving end, the individual signals are extracted from the combined signal by the process of demultiplexing.

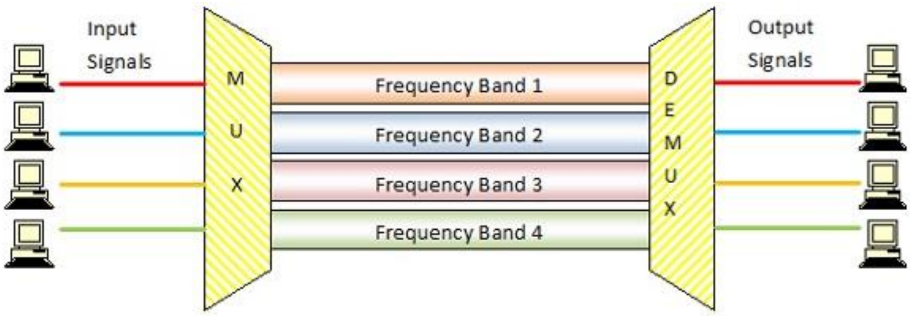


Figure B.2 Frequency division multiplexing technique

1.4 Wavelength Division Multiplexing

WDM is an analogue method of multiplexing where different wavelengths, typically emitted by several lasers are multiplexed in the transmitter by means of passive WDM filters, and likewise they are separated or demultiplexed in the receiver by means of the same filters or coherent detection that usually involves a tunable local oscillator.

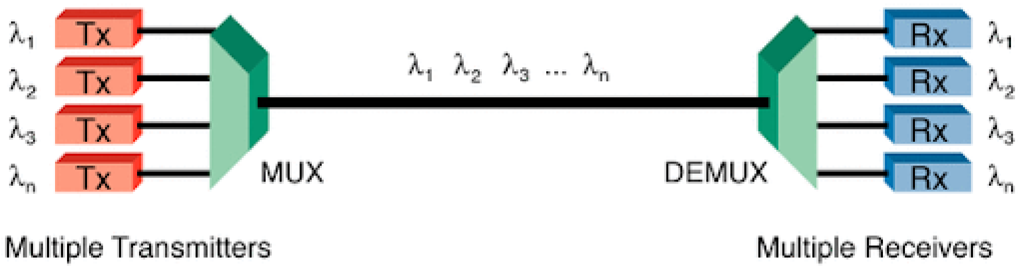


Figure B.3 Wavelength division multiplexing technique

2. DWDM topologies

Dense wavelength division multiplexing (DWDM) networks are categorized into four major topological configurations: DWDM point-to-point with or without add-drop multiplexing (OADM) network, a fully connected mesh network, a star network, and a DWDM ring network with OADM nodes and a hub. Each topology has its own requirements and, based on the application, different optical components may be involved in the respective designs. In addition, there are hybrid network topologies that can consist of stars and/or rings that are interconnected with point-to-point links.

2.1 Point-to-point network topology

Point-to-point topology is primarily for long-haul transport that requires ultrahigh speed (10 - 40 Gb/s), ultrahigh bandwidth, high signal integrity, great reliability, and fast path restoration capability. The distance between transmitter and receiver can be several hundred kilometers, and the number of amplifiers required between the end points is typically less than 10. Point-to-point topologies can be implemented with or without add-drop multiplexing that enables the system to drop and add channels along its path.

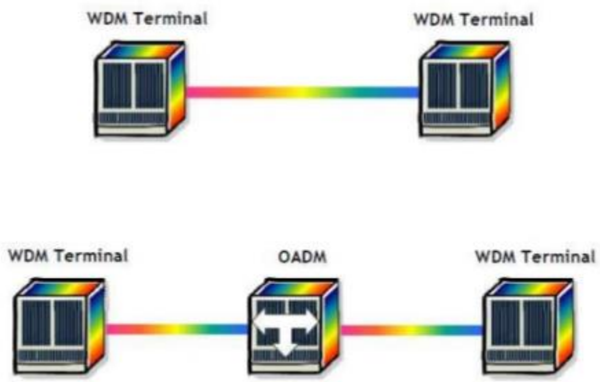


Figure B.4 Point-to-point architecture

2.2 Star network topology

The star topology is considered as the easiest topology to design and implement. It consists of subscribers transceiver nodes which are connected via point to point links to the central node. This topology reduces the chance of network failure by connecting all of the systems to a central node.

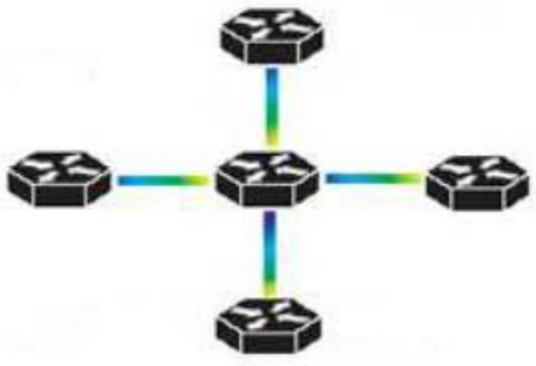


Figure B.5 Star network architecture

2.3 Ring network topology

A DWDM ring network may cover a local or a metropolitan area and span a few tens of kilometers. It consists of a fiber in a ring configuration that fully interconnects nodes; some systems have two fiber rings for network protection. One of the nodes on the ring is a hub station where traffic is originated and managed to connect with other networks. The other nodes are optical add-drop multiplexers (OADM), where the selected wavelengths are dropped and added, while the others pass through transparently. However, as the number of OADMs increases, the signal is subject to losses and optical amplification may be required.

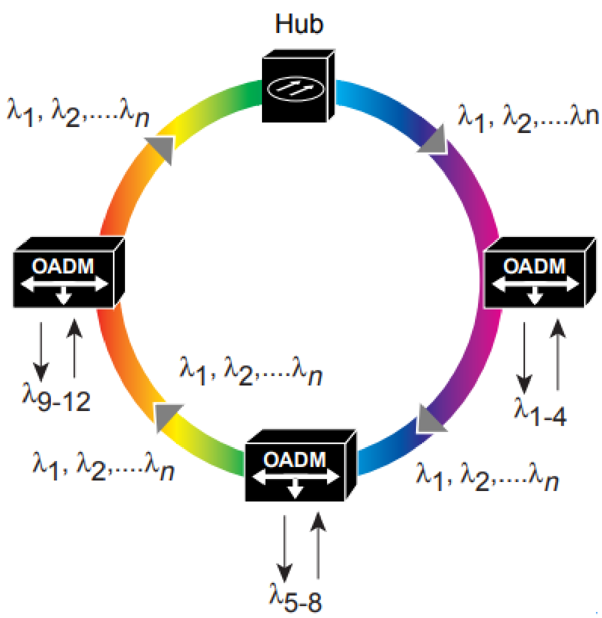


Figure B.6 Ring network architecture

2.4 Mesh network topology

Mesh architectures are the future of optical networks. As networks evolve, rings and point-to-point architectures will still have a place, but mesh promises to be the most robust topology. This development will be enabled by the introduction of configurable optical switches that will in some cases replace and in other cases supplement fixed DWDM devices. From a design standpoint, there is a graceful evolutionary path available from point-to-point to mesh topologies. Starting with point-to-point links, equipped with OADM nodes at the outset for flexibility, and subsequently interconnecting them, the network can evolve into a mesh without a complete redesign. Additionally, mesh and ring topologies can be joined by point-to-point links, as shown in figure B.7.

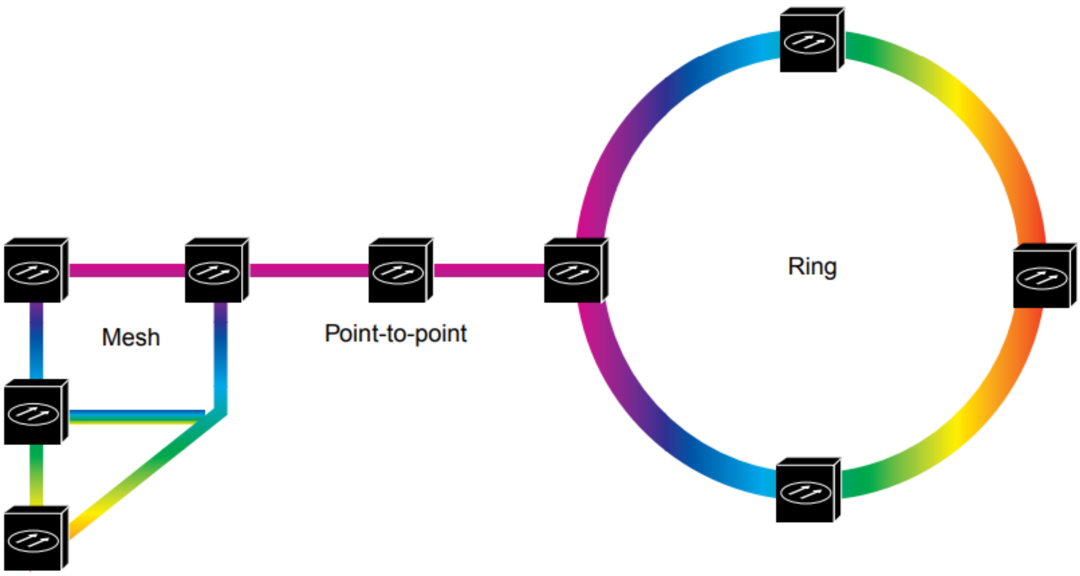


Figure B.7 Mesh, Point-to-Point and Ring architectures

3. Optical amplifier types

3.1 Erbium Doped Fiber Amplifier (EDFA)

An EDFA is an optical amplifier mainly made of erbium element doped to the core of the optical fiber, pump light source, optical couplers, optical isolators, optical filters and other components. A weak signal enters the EDFA, into which light at 980 nm or 1480 nm is injected using a pump laser. This injected light stimulates the erbium atoms to release their stored energy as additional 1550 nm light. As a result, the signal strength grows stronger down the fiber.

It is characterized by the high gain, low noise, polarization independence, and capability to amplify optical signals in the 1.55 μm or 1.58 μm bands. However, it can not be integrated with other semiconductor devices and suffers from its big size.

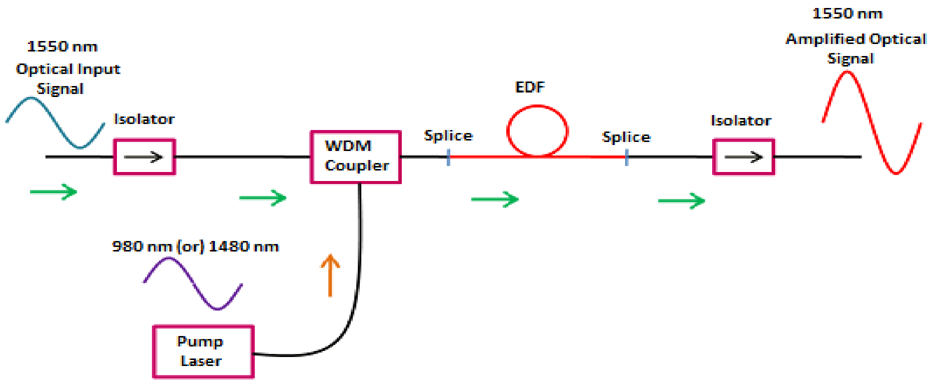


Figure B.8 EDFA configuration

3.2 Raman Amplifier (RA)

In Raman amplifier, the optical signal is amplified due to the non-linear stimulated Raman scattering (SRS) which converts the energy of short-wavelength pump light into the energy of long-wavelength signal light. It operates around 1330 nm and 1550 nm with pumps at 1240 nm and 1420 nm respectively. It is mainly used to amplify the optical signal band of which EDFA cannot satisfy with more pump power. The pump photon has to lose its energy to create another photon at a lower frequency (higher wavelength) and lower energy. The difference in energy creates optical phonons, which are absorbed by the medium.

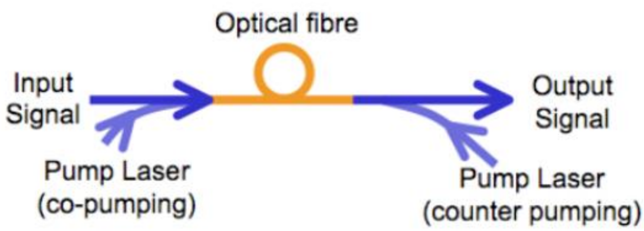


Figure B.9 Raman amplifier configuration

3.3 Semiconductor Optical Amplifier (SOA)

SOA has a similar structure of laser diode but with anti-reflection design elements at the end faces. By performing anti-reflective processing on the cleavage plane of a semiconductor laser and eliminating the resonator structure, light can enter from outside the semiconductor and be amplified via stimulated emission.

Unlike other optical amplifiers SOAs are pumped electronically (i.e. directly via an applied current), and a separate pump laser is not required which means that it can be run with a low power laser. When light traveling through the active region causes the excited electrons to get back to their ground state, they lose their energy in the form of photons. Those stimulated photons have the same wavelength as the optical signal, thus amplifying the optical signal.

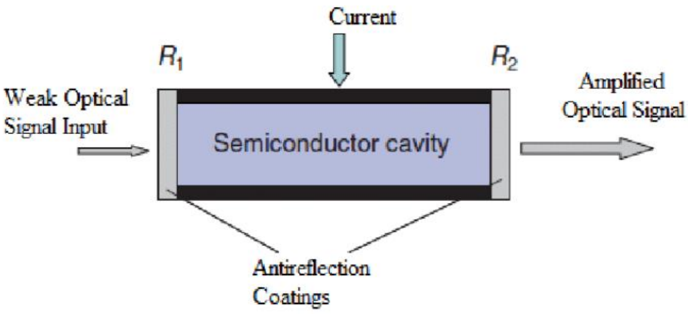


Figure B.10 SOA configuration

A comparison between the three optical amplifiers is summarized in the table B.1 below:

Table B.1 Comparison between EDFA, Raman and SOA

Properties	Gain (dB)	Wavelength (nm)	Bandwidth (3dB)	Noise Figure (dB)	Pump power
EDFA	>40	1530-1560	30-60	5	25 dBm
Raman	>25	1280-1650	Pump dependent	5	>30 dBm
SOA	>30	1280-1650	60	8	<400 mA

4. Crosstalk

Crosstalk is the unwanted coupling between signal paths, where the signal from one channel arrives in another, creating interference in that channel. Crosstalk is one of the major limitations in DWDM systems due to its considerable effect on the Optical Signal-to-Noise Ratio (OSNR) and hence on the error rate of the system. Two kinds of crosstalk exist, depending on their source.

4.1 Inter-band crosstalk

It is situated in wavelengths outside the channel slot and can be removed with narrow-band filters. In a DWDM network, inter-band crosstalk appears from channels of different wavelengths.

4.2 Intra-band crosstalk

Intra-band crosstalk is situated within the same wavelength slot. It occurs when the signal and the interferer has closely valued wavelengths. It cannot be removed by an optical filter and therefore accumulates through the network.

1. Types of optical splices

Splicing of optical fibers is a technique used to join two fibers together**.** This technique is used in fiber communication, in order to form long optical links for a better and a long-distance optical signal transmission. Optical splices are divided into two categories:

- **Fusion splices**

  They are junctions of two or more optical fibers that have been melted together. This is accomplished with a machine called fusion splicer that performs two basic functions: aligning of the fibers and melting them together, typically using an electrical arc.

- **Mechanical splices**

  They are simply alignment devices and don't permanently join two fibers together, designed to hold the two fiber ends in a precisely aligned position thus enabling light to pass from one fiber into the other.

2. Eye diagram

It is used in electrical engineering to get a good idea of signal quality in the digital domain. 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. The eye diagram is used primarily to look at digital signals for the purpose of recognizing the effects of distortion and finding its source.

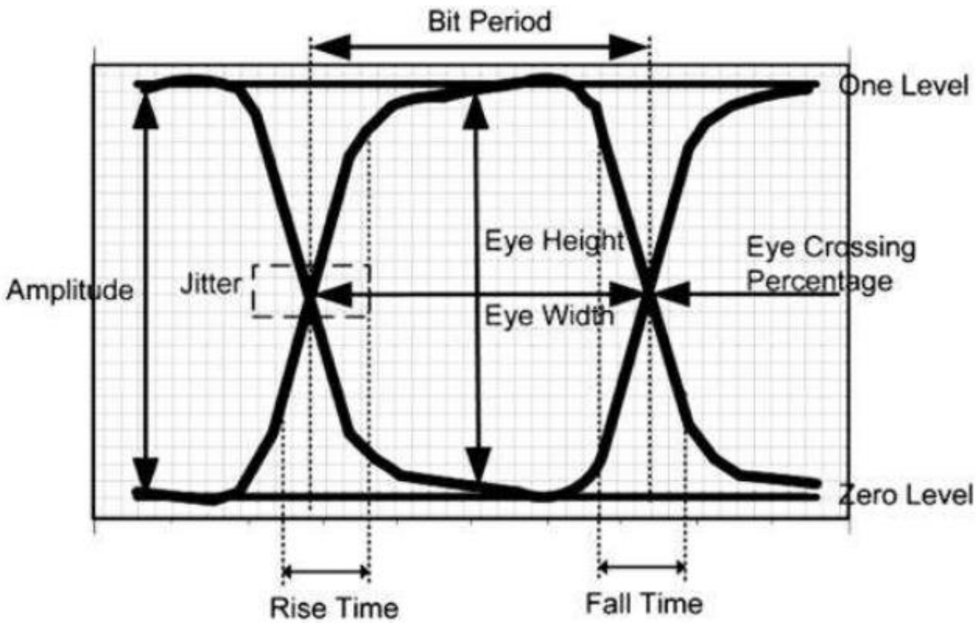


Figure C.1 Example of an eye diagram

The measurements are defined as follows:

- **One Level**
  It 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**
  It 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**
  It is the difference between the one and zero levels. The data receiver logic circuits will determines whether a received data bit is a “0” or “1,” based on the eye amplitude.

- **Eye Height**
  It 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.

- **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 10 and 90% levels of the slope.

- **Fall Time**
  It 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 10 and 90 percent levels of the slope.

- **Jitter**
  It is the time deviation from the ideal timing of a data-bit event.

- **Eye Crossing Percentage**
  It is the mean value of a thin vertical histogram window centered on the crossing point of the eye diagram.

- **Bit Period**

  It is a measure of the horizontal opening of an eye diagram at the crossing points of the eye

- **Eye Width**

  It 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.

1. OTDR components

The OTDR injects light energy into the fiber through a laser diode and a pulse generator. A coupler fed to the photodiode separates the returning light energy from the injected signal. The optical signal is converted to an electrical value, amplified, sampled and displayed on the screen.

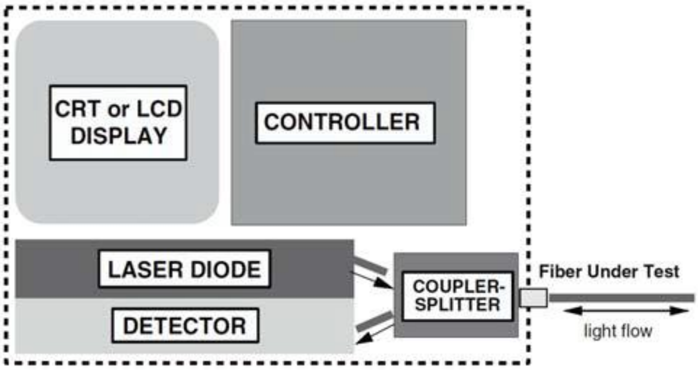


Figure D.1 OTDR schematic diagram

1.1 Laser light source

It sends out pulses of light on command from the controller. The duration of the pulse (the Pulse Width) can be selected for different measuring conditions. Some OTDRs have two lasers to allow for testing fibers at two different wavelengths. Only one laser is used at a time. Switching between the two is done easily by pressing a button.

1.2 Coupler

It has three ports, one for the source, the fiber under test, and the sensor. It allows light to travel only in specific direction, from the laser source to the fiber under test, and from the fiber under test to the sensor. Light is not allowed to go directly from the source to the sensor. Thus the returning backscatter and Fresnel reflections are routed to the sensor.

1.3 Optical sensor (detector)

It's a photodiode that measures the power level of the light coming from the fiber under test. It converts the optical power in the light to a corresponding electrical level .The higher the optical power, the higher the electrical level put out. OTDR sensors are specially designed to measure the extremely low levels of backscattered light. The sensor section includes an electrical amplifier to further boost the electrical signal level.

1.4 Control unit

It tells the laser when to pulse, it gets the power levels from the sensor, it also calculates the distance to scattering and reflecting points in the fiber. In addition, it stores the individual data points and it sends the information to the display section.

1.5 Display unit

The display unit is a CRT or LCD screen that shows the data points that make up the fiber trace, and displays the OTDR set-up conditions and measurements. Most OTDR displays connect the data points with a line to provide a clearer look at the overall trace. Cursors can be manipulated on the screen to select any point on the fiber trace.

2. OTDR specifications

2.1 Dynamic range

It is a physical quantity measured in dB, used to determine the maximum length of fiber that the longest pulse can reach. The higher the dynamic range, the higher the signal-to-noise ratio and the clearer the display will be, and the better the event detection. Connectors, splices and splitters are some of the factors that reduce the maximum length of an OTDR. Therefore, averaging for a longer period of time and using the proper distance range is the key to increase the maximum measurable distance.

The dynamic range can be determined by taking the difference between the extrapolated point of the backscatter trace at the near end of the fiber (taken at the intersection between the extrapolated trace and the power axis) and the upper level of the noise floor at (or after) the fiber end.

Depending on the noise level reference, there are many methods to calculate the dynamic range. The first method describes the “98% Noise Level” method recommended by many standards organizations. It describes the point at which the backscatter level just starts to get mixed up with the noise level of the instrument. Another common method is called “SNR=1” (Signal-To-Noise Ratio), which is similar to the 98% method, but produces a dynamic range value of about 1.56 dB more. The SNR=1 method indicates the point at which the backscatter level of the trace is lower down into the instrument’s internal noise level. The third method gives an idea of the limit to which the OTDR can measure when the noise level is 0.1 dB on the trace. The difference between N=0.1 and SNR=1 RMS definition is approximately 6.6 dB.

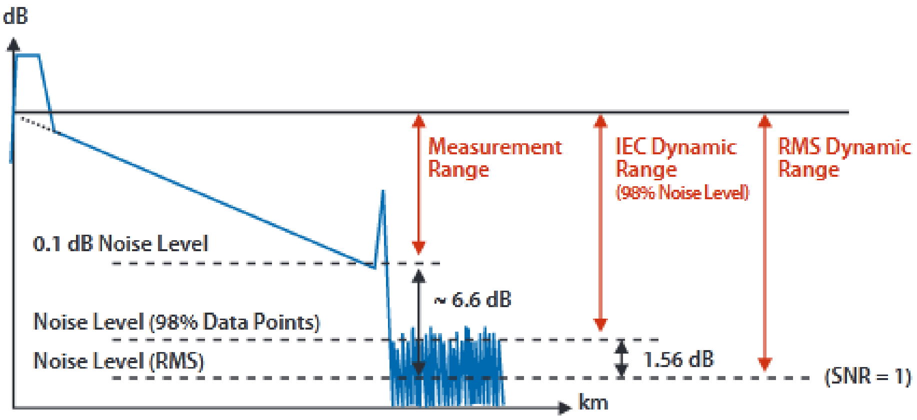


Figure D.2 Different definitions of the dynamic range

2.2 Dead zone

A dead zone is defined as the distance (or time) where the OTDR cannot detect or precisely localize any event or artifact on the fiber link due to Fresnel reflection (mainly caused by air gap at the OTDR connection).

When a strong reflection occurs, the power received by the photodiode can be more than 4000 times higher than the backscattered power, saturating the photodiode. Thus, it needs time to recover from its saturated condition. During the recovering time, it cannot detect the backscattered signal accurately which results in corresponding dead zone on OTDR trace.
In general, dead zones on an OTDR trace can be divided into event dead zone and attenuation dead zone.

a) **Event dead zone (EDZ)**

The event dead zone is the minimum distance after a Fresnel reflection where an OTDR can detect another event. In other words, it is the minimum length of fiber needed between two reflective events where the consecutive event can be detected but the loss can't be measured. To establish specifications, the distance is measured between two opposite points that are 1.5 dB (or full width at half maximum FWHM) down from the unsaturated peak of a single reflective event. The purpose of the EDZ specification is to provide an indication of the distance after a connector at which an accurate length measurement can be made.

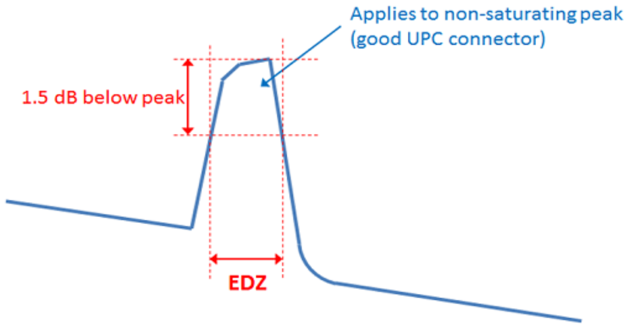


Figure D.3 Event dead zone

b) Attenuation dead zone (ADZ)

The attenuation dead zone is the minimum distance after a Fresnel reflection where an OTDR can accurately measure the loss of a consecutive event. The detector has enough time to recover so that it can detect and measure the loss of the consecutive event. The minimum required distance is measured from the beginning of a reflective event until the reflection is back to 0.5 dB over the fiber's backscattering level. The purpose of the ADZ specification is to provide an indication of the distance after a connector at which an accurate loss measurement can be made.

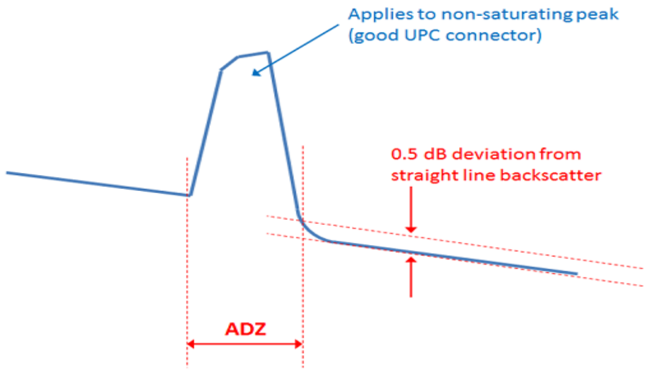


Figure D.4 Attenuation dead zone

Specifications use the shortest pulse width in order to provide the shortest dead zones. However, dead zones are not always the same length; they stretch as the pulse width increases. Using the longest possible pulse width results in extremely long dead zones.

2.3 Resolution

The four main types of resolution parameters are display (cursor), loss (level), sampling (data point), and distance.

a) Display resolution

There are two types of display resolution which are: readout and cursor. Readout display resolution refers to the minimum resolution of the displayed value. For example, an attenuation of 0.031 dB will have a resolution of 0.001 dB. The cursor display resolution refers to the minimum distance, or attenuation, between two displayed points. A typical cursor display resolution value is 1 cm or 0.001 dB.

b) Loss resolution

Governed in general by the resolution of the acquisition circuit, it specifies the minimum loss change that can be measured.

c) Sampling resolution

Sampling (or data point) resolution refers to the minimum distance between two acquisition points, depending on pulse width and range. The more data points, the better the sampling resolution. Therefore, the number of data points that an OTDR can acquire is an important performance parameter. A typical high resolution OTDR may have a sampling resolution of 1 cm.

d) Distance resolution

Distance resolution is very similar to Sampling Resolution where it depends on pulse width and range. It determines the ability of the OTDR to locate an event, for example if the Distance Resolution of an OTDR is 8 cm then the fiber end location should be within + or -8 cm.

2.4 Accuracy

The accuracy of a measurement refers to its capacity to be compared with a reference value.

a) Attenuation accuracy (linearity)

The linearity of the acquisition circuit determines how close an optical level corresponds to an electrical level across the entire range. Most OTDRs have an attenuation accuracy of ±0.05 dB/dB. If an OTDR is nonlinear, the section loss values will change significantly for long fiber.

b) Distance accuracy

Usually determined by the sampling resolution (distance between successive points making up the OTDR trace) and uncertainties in the value of group index (propagation velocity) of the fiber being measured.

2.5 Wavelengths

Fibers are tested at the same wavelengths that are used for transmission**.** The main wavelengths for OTDR are 850 and 1300 nm for multimode fibers and 1310, 1550, and 1625 nm for single mode fibers.

A 1625 or 1650 nm laser diode can be used for remote monitoring systems or in fiber-to-the home (FTTH) passive optical network (PON) applications. The purpose of using these wavelengths is to avoid interference with traffic at 1310 nm and around 1550 nm.

There are other wavelengths for fiber characterization which are:

- 1383 nm wavelength used for attenuation measurements around the main fiber absorption peak.
- 1420, 1450, and 1480 nm wavelengths used for Raman-amplified systems.
- 1490 nm wavelength used for FTTH systems.
- 1271 to 1611 nm coarse wavelength division multiplexing (CWDM) wavelengths used for OTDRs dedicated to CWDM system turn-up and troubleshooting.

3. Optical fiber cable

An optical fiber cable is made up of several optical fibres bundled together, which are usually covered in individual protective covers to reduce losses and damage, as shown in figure D.5.

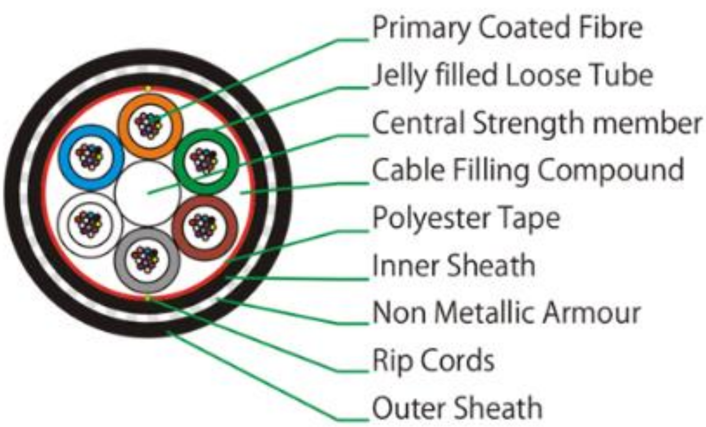


Figure D.5 Typical cross section of optical cable

3.1 Different structures of fiber optic cables

Fiber optic cables are available in many physical variations, such as single and multiple conductor constructions, aerial and direct burial styles, plenum and riser cables, etc. But there are two basic styles of fiber optic cable structure: loose tube cable and tight buffered cable.

a) Loose tube cables

Loose tube cables are designed for harsh environmental conditions in the outdoors. This type of cables contains coated fibers which are placed loosely within a plastic tube whose inner diameter is considerably larger than the fiber itself. Usually 6 to 12 fibers are placed within a single tube. The interior of the plastic tube is usually filled with a gel material that protects the fibers from moisture and physical stresses that may be experienced by the overall cable. Since the fiber is not under any significant strain, loose buffer tube cables exhibit low optical attenuation losses. Although loose tube gel filled fiber optic cables are used for high fiber count and long-distance applications, they are an inferior design for the Local Area Network (LAN) applications where reliability, attenuation stability over a wide temperature range and low installed cost are the priorities.

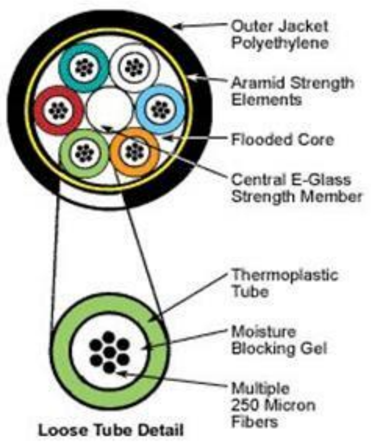


Figure D.6 Loose tube cable structure

b) Tight buffer cables

In contrast to loose tube cables, tight buffer cables are optimized for indoor applications. This sort of cables uses a two-layer coating instead of the gel layer, one is plastic and the other is waterproof acrylate. So tight buffered cables may be easier to install, because there is no gel to clean up and it does not require a fan out kit for splicing or termination. Although the fiber is not free to “float”, tensile strength is not as great. Tight buffer cable is normally lighter in weight and more flexible than loose-tube cable and is usually employed for less severe applications. Such applications include moderate distance transmission for LAN and point-to-point links in cities, buildings, factories, office parks and on campuses.

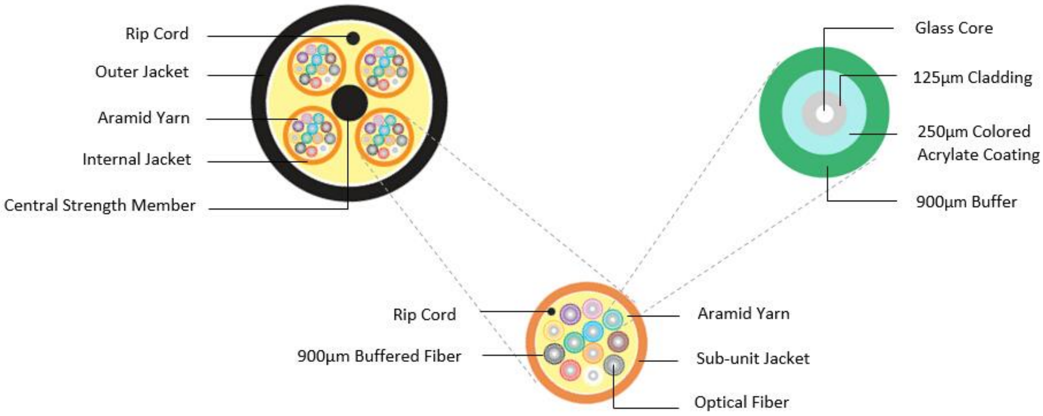


Figure D.7 Tight buffer cable structure

3.2 Special standards for single-mode optical fiber

G652: The first single-mode fiber standard specified by the ITU-T. Its zero dispersion point is in 1300 nm and it's divided into G.652.A, B, C, D. Both of G.652.A and G.652.B have a water peak, and are designed to have a zero-dispersion wavelength near 1310 nm, so they are optimized for operation in the 1310nm band. Whereas, G.652.C and G.652.D feature reduced water peak that allows them to be used in the wavelength region between 1310 nm and 1550 nm supporting Coarse Wavelength Division Multiplexed (CWDM) transmission.

G653: It defines the dispersion-shifted single-mode fiber which exhibits a zero-dispersion value around the 1550nm wavelength where the attenuation is minimum. It is divided into G.653.A and G.653.B, both functioning in the wavelength 1550nm region, and could function around 1310 nm on condition that the attenuation coefficient performs below 0.55 dB/km. Now G.653 fiber is rarely deployed and has been superseded by G.655 fiber for WDM applications, the reason is channels allocated near 1550 nm in G.653 fiber are seriously affected by noise induced as a result of nonlinear effects caused by Four-Wave Mixing.

G654: It covers cut-off shifted single-mode optical fibers which are optimized for operation in the 1500 nm to 1600 nm region. It includes five revisions which are G.654.A, G.654.B, G.654.C, G.654.D, and G.654.E. G.654.A, G.654.B, G.654.C, and G.654.D fibers are suitable for extended long-haul undersea applications. Whereas, G.654.E fiber is designed for high-speed long-haul terrestrial optical networks.

G655: It defines the non-zero dispersion-shifted single-mode optical fiber with performance specified at 1550 nm and 1625 nm. It is divided into five categories: G.655.A, G.655.B, G.655.C, G.655.D, and G.655.E. These fibers were originally intended for use at wavelengths in the range of 1530 to 1565 nm, but provisions can be made to support at wavelengths up to 1625 nm and down to 1460 nm. G.655 fibers were popular before 2005 for WDM and long-distance cable runs, suited for long-haul and backbone applications. But it falls into disuse and is replaced by G.652.D fiber.

G656: It has been dedicated for use in broadband systems using both DWDM and CWDM, intended for use in 1460 nm to 1625 wavelength windows. The attenuation of G.656 fiber is low at 1460nm -1625nm, but when the wavelength is less than 1530nm, the dispersion is too low for the WDM system. So G.656 fiber is not suitable for applications operating from 1460nm to 1530nm.

G657: It is the latest edition of single-mode optical fiber standard and specifies the characteristics of bend-insensitive single-mode optical fibers. G.657 fibers are mainly applied for broadband optical access networks. There exist two categories of the ITU-T G.657: G.657.A and G.657.B.

G.657.A fiber is compliant with the existing ITU-T G.652.D, but offers approximately ten times better macrobending performance. G.657.B is truly bend-insensitive class, with hundreds of times better than traditional single-mode fibers and about ten times better than class G.657.A. G.657.B fiber does not conform with any former ITU-T standard. G.657.A and G.657.B can be further divided into G.657.A1, G.657.A2, G.657.B2, and G.657.B3, distinguished by their macrobending requirements. G.657.A2 and G.657.B3 have better macrobend performance than G.657.A1 and G.657.B2 fibers.

4. Optical connectors types

The acronyms SC, LC, FC and ST refer to the most common types of optical connectors in FTTH applications and data networks. As for the PC/UPC/APC terminology, it refers to the type of polishing applied to the optical terminal (ferrule) which makes possible laser light pulses to cross through two optical fibers. Then, for example, a typical FTTH pigtail with an SC/APC connector used for fusion splicing is referring to an SC connector with an APC polishing.

Generally speaking, the fiber connector can be categorized according to different standards like the popularity, the transmission method, the transmission media, the polishing type and the termination way. The most five commonly used connectors are:

a) **LC connector**

A Lucent Connector (LC), as one SFF (small form factor) connector, possesses a 1.25 mm ferrule. The small footprint design gives these connectors huge popularity in datacoms and makes them more ideal for high-density applications. Many tend to move to high-efficiency cabling with LC fiber connectors nowadays.

b) **SC connector**

Stands for "Square Connector" due to the "square-shaped" connector body. It adopts a 2.5mm ferrule, which is twice the size of the previous LC connector. SC fiber connector is ideally suited for datacoms and telecom applications including point to point and passive optical networking, due to its excellent performance.

c) **MTP/MPO connector**

Unlike the previous two, the MTP/MPO fiber connector is a multi-fiber connector and larger than other connectors, which combines fibers from 12 to 24 fibers in a single rectangular ferrule. It's often used in 40 G and 100 G high-bandwidth optical parallel connections.

d) **ST connector**

Straight Tip (ST) fiber connector holds the fiber with a ceramic, spring-loaded 2.5mm ferrule that stays in place with a half-twist bayonet mount. They are usually used in both long and short distance applications such as campuses and building multimode fiber applications, corporate network environments, as well as military applications.

e) **FC connector**

Refers to the Ferrule Connector. It was the first optical fiber connector to use a ceramic ferrule. Unlike the plastic-bodied SC and LC connectors, it utilizes a round screw-type fitment made from nickel-plated or stainless steel. The FC connector end face relies on an alignment key for correct insertion and is then tightened into the adaptor/jack using a threaded collet. Despite the additional complexity both in manufacturing and installation, the FC connectors still provide the choice in precision instruments such as OTDRs, as well as the choice for single mode fiber. It was initially intended for datacoms and telecoms applications but was used less since the introduction of the SC and LC. The usage of both ST and FC connectors have declined in recent years.

According to the polishing type, optical fiber cable connectors can be divided into three types: PC, UPC, and APC connectors. The color code provides a convenient method to identify these three types of connectors: PC's color code is black, the color code for the APC fiber connector is green, and the UPC's connector is blue. The structure and the performance of the three fiber optic connectors also vary, which reflects on the values of insertion loss and return loss. Among them, APC tends to become the preferred polishing type.