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In Telecommunications Systems

Entitled

Modeling and Simulation of Optical Transport Networks in Telecoms

Presented by: **HAMADOUCHE Hadjira**

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I dedicate this work to my parents,

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With love and gratitude.

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List of Publications

This thesis is based on the following appended papers:

Paper A **Hadjira Hamadouche**, Boualem Merabet and Mouweffeq Bouregaa, ''The performance comparison of hybrid WDM/TDM, TDM and WDM PONs with 128 ONUs'' , *J.Opt.comm 2020* ;aop,doi.org/10.1515/joc-2020-0046, Publisher : Walter de Gruyter, June29, 2020. (impact Score : 1.36)

Paper B **Hadjira Hamadouche**, Boualem Merabet and Mouweffeq Bouregaa,'' Performance Analysis Of WDM PON Systems Using PIN And APD Photodiodes'' , *Int. J. Computer Aided Engineering and Technology* , accepted :03 /05/2020 .(impact Score : 0.48)

Paper C **Hadjira Hamadouche** , Boualem Merabet , Mouweffeq Bouregaa and Samir Ghouali , ''Performance analysis of TDM PON system for 128 users using RZ and NRZ modulations'' *Int. J. Computer Aided Engineering and Technology* , accepted :29 mai 2020,(impact Score : 0.48)

Paper D **Hadjira Hamadouche** , Mouweffeq Bouregaa , Boualem Merabet , Samir GHOUALI , Abdelfettah MIRAOUI and Mohammed MOULAY '' Numerical simulation of High Speed Optical Local Area Networks '', *The international Conference on Intelligent Systems and Advanced Computing Sciences(ISACS'19), Taza ,Morooco*,26 December 2019 ,978-1-7281- 4813-7/19/$31.00©2019 IEEE, DOI: 10.1109 /ISACS 48493. 2019. 9068869, (indexed by Scopus)

Paper E **Hadjira Hamadouche** , Boualem Merabet and Mouweffeq Bouregaa , '' Performance Comparison of APD and PIN Photodiodes using RZ and NRZ'',*The Electrical Engineering International Conference EEIC'19,Bejaia,Algeria* 4 December 2019.

Paper F **Hadjira Hamadouche**, Boualem Merabet and Mouweffeq Bouregaa , '' Performance Analysis And Improvement Of (2-10) Gbps WDM PON using EDFA amplifiers '', *The First IEEE International Conference On Communication,Control systems And Signal Processing (CCSSP 2020),El oued-Algeria*,16 Marh 2020 ,978-1-7281-5835-8/20/$31.00 ©2020 IEEE , DOI: 10.1109/CCSSP49278.2020.9151806.

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Paper H Bouregaa Mouweffeq , Debbal Mohammed, Ghouali Samir ,Baba Ahmed Mohammed Zakarya, Miraoui Abdelfettah, , **Hamadouche Hadjira**,''Optical Local Area Network Performance Analysis Using Optisystem Software'',*5th International Conference On Advances In Mechanical Engineering Istanbul 2019(ICAM 2019)* ,17 December 2019.

Paper I Nabil Cherif, Mehadji Abri, Benzerga Fellah, Hadjira Badaoui, **Hamadouche Hadjira**, ''4G LTE Radio Network analysis, Design and Simulation'', *Conference: Conférence Nationale sur les Télécommunications et ses Applications (CNTA'21)*At: Ain-Témouchent, Algeria, December 2021

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Résumé

Transmettre systématiquement de l'information sur un support optique, telle que la fibre, est le but majeur des réseaux de transport optique (OTN) en télécoms, comprenant des capacités /fonctionnalités de réseau, en plus des technologies nécessaires pour les prendre en charge. Les aspects relatifs aux synchronisations/distributions temporelles dans les technologies de tels réseaux sont aussi inclus dans leur définition. Le focus de cette thèse de doctorat sera le transport et la mise en réseau des charges utiles des clients numériques sur des câbles à fibres optiques. Bien que les mécanismes de transport optique (OTN, hiérarchie numérique synchrone (SDH), trames Ethernet sur le transport (EoT), profil de transport 'commutation d'étiquettes multi-protocole' (MPLS-TP)) établis dans le plan de transport) relèvent d'une grande importance en matière de réseaux, les efforts de normaliser les fonctionnalités des OTN, EoT et MPLS-TP doivent être pris en compte. Les aspects relatifs à la gestion du plan de commande et des équipements associés, notamment les réseaux optiques à commutation automatique (ASON) et les réseaux définis par des logiciels (SDN), ayant de vastes champs d'applications, entrent aussi dans le cadre de cette thèse.

Mots clés

Fibre optique, portées optiques/amplificateurs, réseau de transport optique (OTN), hiérarchie numérique synchrone (SDH), réseau défini par logiciel (SDN), commutation par étiquette multiprotocole - profil de transport (MPLS-TP), réseau optique à commutation automatique (ASON).

Abstract

Systematically transmitting information over an optical medium, such as fiber, is the major goal of optical transport networks (OTNs) in telecom, including network capabilities/functions, in addition to the technologies needed to support them. Aspects related to time synchronization/distribution in such network technologies are also included in their definition. The focus of this PhD thesis will be the transport and networking of digital client payloads over fiber optic cables. Although the optical transport mechanisms (OTN, Synchronous Digital Hierarchy (SDH), Ethernet over Transport (EoT), Multi-Protocol Label Switching Transport Profile (MPLS-TP)) established in the transport plane are of great importance in networking, the efforts to standardize the functionalities of OTN, EoT and MPLS-TP need to be taken into account. Aspects of control plane management and associated equipment, including Automatically Switched Optical Networks (ASONs) and Software Defined Networks (SDNs), with broad application areas, are also within the scope of this thesis.

Key words

Optical fiber, Optical spans/Amplifiers, Optical Transport Network (OTN), Synchronous Digital Hierarchy (SDH), Software-defined networking (SDN), Multi-protocol label switching-transport profile (MPLS-TP), Automatically Switched Optical Network (ASON).

الملخــــــص

يعد نقل المعلومات بشكل منهجي عبر وسيط ضوئي ، مثل الألياف ، هو الهدف الرئيسي لشبكات النقل البصري (OTN) في الاتصالات ، والتي تشتمل على قدرات / وظائف الشبكة ، بالإضافة إلى التقنيات اللازمة لدعمها. كما يتم تضمين الجوانب المتعلقة بمزامنة / توزيعات الوقت في تقنيات هذه الشبكات في تعريفها. سينصب تركيز أطروحة الدكتوراه هذه على نقل حمولات العميل الرقمية وتوصيلها عبر كبلات الألياف البصرية. على الرغم من أن آليات النقل البصري (OTN) ، التسلسل الهرمي الرقمي المتزامن (SDH)، Ethernet-over-Transport (EoT)، ملف النقل 'Multi-Protocol Label Switching' (MPLS-TP)) التي تم إنشاؤها في مستوى النقل) لها أهمية كبيرة في الشبكات ، والجهود المبذولة لتوحيد وظائف OTN و EoT و MPLS-TP يجب أن تؤخذ في الاعتبار. تقع أيضًا الجوانب المتعلقة بإدارة مستوى التحكم والمعدات المرتبطة به ، ولا سيما الشبكات البصرية المحولة تلقائيًا (ASON) والشبكات المعرفة بالبرمجيات (SDN) ، والتي لها مجالات تطبيق واسعة ، ضمن نطاق هذه الأطروحة.

الكلمات الدالة

الألياف الضوئية ، الامتدادات / المضخمات الضوئية ، شبكة النقل البصري (OTN) ، التسلسل الهرمي الرقمي المتزامن (SDH) ، الشبكات المعرفة بالبرمجيات (SDN) ، ملف تعريف النقل متعدد البروتوكولات (MPLS-TP) ، الشبكة البصرية المحولة تلقائيًا (ASON)).

Abbreviations in the Text

ADC	Analog-To-Digital Conversion
APD	Avalanche Photodiode
AN	Access Nodes
ASE	Amplified Spontaneous Emission
AWG	Array Waveguide Grating
BER	Bit Error Rate
BPF	Band Pass Filter
BPON	Broadband Passive Optical Network
CCR	Conventional Correlation Receiver
CDMA	Code-Division Multiple Access
CFBG	Chirped Fiber Bragg Grating
CW	Continuous Wave
CWDM	Coarse Wavelength Division Multiplex
DCF	Dispersion-Compensating Fiber
DEB	Distributed Bragg Reflector
DF	Diffraction Grating Filter
DFP	Distributed Feedback
DFT	Discrete Fourier Transform
DGD	Differential Group Delay
DRBS	Double Rayleigh Back Scattering
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexed
EDFA	Erbium-Doped Fibers Amplifier
FBG	Fiber Bragg Grating
FDM	Frequency-Division Multiplexing
FDMA	Frequency-Division Multiple Access
FP	Fabry-Perot
FPA	Fabry–Perot Amplifiers
FSO	Free-Space Optics
FSR	Free Spectral Range
FTTC	Fiber-To-The- curb
FTTH	Fiber-To-The-Home
FWM	Four-Wave Mixing
GaInAsP	Gallium Indium Arsenide Phosphide
GEO2	Germanium Dioxide
GPON	Gigabit Passive Optical Networks
GVD	Group Velocity Dispersion
HL+CCR	Hard Limiter Conventional Correlation Receiver
IDFT	Inverse Discrete Fourier Transform
ISI	Intersymbol Interference
ITU	International Telecommunication Union
LAN	Local Area Network
LiNbO3	Lithium Niobate
LO	local oscillator
LPBF	Low Pass Bessel Filter

LPF	Low-pass filter
MEMS	Micro-Electro-Mechanical System
MMF	Multi-Mode Fibers
MPLS-TP	Multi-Protocol Label Switching Transport Profile
MZ	Mach-Zehnder
NA	Numerical Aperture
NF	Noise Figure
NGA	Next Generation Access
NOLM	Nonlinear Optical Loop Mirror
NRZ	Non-Return-To-Zero
NZ-DSF	Non-Zero Dispersion-Shifted Fiber
OC	Optical Carrier
OCDM	Optical code division multiplexing
OCS	Optical Carrier Suppression
ODN	Optical Distribution Networks
OFC	Optical fiber communication
OFDM	Orthogonal Frequency-Division Multiplexing
OLAN	Optical Local Area Networks
OLT	Optical Line Terminals
ON	Optical Network
ONT	Optical Network Terminal
ONU	Optical Network Unit
OOC	Optical Orthogonal/pseudo orthogonal codes
OS	Optical Switches
OSNR	Optical Signal-to-Noise Ratio
OTDM	Optical Time-Division Multiplexing
OTN	Optical Transport Network
P2M	Point To Multipoint
PC	Prime Codes
PCM	Pulse Code Modulation
PDH	Plesiochronous Digital Hierarchy
PG	Pulse Generator
PIC	Photonic Integrated-Circuit
PIC	Parallel Interference Cancellation
PIN	Positive Intrinsic Negative Photodiode
PMD	Polarization Mode Dispersion
PON	Passive Optical Networks
PRBSG	Pseudo Random Bit Sequence Generator
PSD	Spectral Density Of Power
PSTN	Public Switched Telephone Networks
Q factor	Quality (Q) Factor
QPSK	Quadrature Phase-Shift Keying
RF	Radio Frequency
RFA	Raman Fber Amplifiers
RI	Refractive Index
ROADM	Reconfigurable Optical Add-Drop Multiplexer
ROF	Radio over fiber
RZ	Return-To-Zero
SBS	Stimulated Brillouin Scattering
SDH	Synchronous digital hierarchy

SDN	Software Defined Networking
SMF	Single Mode Fibers
SNR	Signal-To-Noise Ratio
SOA	Semiconductor Optical Amplifiers
SONET	Synchronous Optical Network
SPM	Self-Phase Modulation
SRBS	Single Rayleigh Back Scattering
SRS	Stimulated Raman scattering
SSMF	Standard Single-Mode Fiber
STM	Synchronous Transport Modules
STS	Synchronous Transport Signal leve
TDM	Time-Division Multiplexing
TDMA	Time-Division Multiple Access
TE	Transverse Electric
TFF	Thin-Film Filter
TIR	Total Internal Reflection
TM	Transverse Magnetic
TOD	Third-Order Dispersion
TPS	Triple-play services
TWA	Traveling Wave Amplifiers
UDWDM	Ultra Dense Wavelength Division Multiplex
VDSL	Very-high-bit-rate Digital Subscriber Line
WDM	Wavelength Division Multiplexed
WGR	Wave Guide-Grating Router
WSC	Wavelength Selective Coupler
WWDM	Wide Wavelength Division Multiplex
XGM	Cross Gain Modulation
XPM	Cross Phase Modulation

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General Introduction

Communication systems send data between locations, whether distances are few kilometers or thousands of kilometers, in the way that using dielectric waveguides comprising glasses to transmit wide band telecommunication signals was sparked by the enormous potential bandwidth of optical communications [1]. Electromagnetic carrier waves, of frequencies ranging from a few mega hertz to several hundred terahertzes, usually transport data, so that high carrier frequencies (e.g. 100THz) in the visible or near IR region of the electromagnetic spectrum are used in optical communication systems [2]. Since 1854, the total internal reflection phenomenon (responsible for light guiding in optical fibers) has been known, and optical fibers were mostly utilized for medical imaging at short distances before 1970, though glass fibers were invented in the 1920s and not exploited until the 1950s where their usage became practical [2]. Due to enormous losses (1000dB/km), their usage for communication was regarded impractical, when losses of optical fibers were lowered to less than20 dB/km in 1970 [3]. The situation had dramatically changed such as by 1979, improvements had resulted in just 0.2 dB/km as losses at the 1.55μm spectral region [2].

Optical fibers are widely considered as primary components of all future high-capacity residential broad band networks, so as their transmission capacity is nearly limitless and unconditional compared to traditional copper cabling systems [4]. There is minimal difference in deploying costs of optical fiber and copper cable networks of equivalent capacity, however, optical fibers can provide high bandwidth and future upgrade possibilities across long distances, and not require significantly expansive maintenance and operating costs, which make them a perfect choice [5].

The design of passive optical networks (PONs) was proposed as an approach to share the enormous fiber data transfer capacity among numerous clients through an aloof splitter, and latterly improve the per client cost of optical LAN [6]. Working on PONs standardization began in the 1990s when carriers anticipated fast growth in bandwidth demands[7].Systematically transmitting information over an optical medium, such as fiber, is the major goal of optical transport networks (OTNs) in telecom, Multi-Protocol Label Switching Transport Profile (MPLS-TP)) established in the transport plane are of great importance in networking,where MPLS is a network technique whose main role is to combine the consepts of level 3 IP routing,and the mechanismsof level 2 switching as implemented in ATM or fram Relay.also we have software defined networking (SDN) witch is a networking concept that enables centralized and intelligent management and control of individual hardware.components using software.

Fiber-to-the-home (FTTH) has appeared to be the shining star in the next generation access (NGA) family, as an outstanding platform for high or ultra-high speed access technologies; FTTH solutions can not only assist fixed access networks, but also benefit advanced wireless networks, mainly in terms of improved backhaul capacity [8]. While transiting from copper-based networks to FTTH ones represents a significant change for operators, the issues associated with FTTH implementation and operation have been handled with a plenty of proven solutions for both passive and active elements of networks [9]. FTTH networks will often be integrated into an existing access networks, connecting large numbers of end users to central points (known as access nodes: ANs), that provide the necessary active transmission equipment for delivering applications and services to subscribers through optical fiber; a bigger metropolitan or urban network fiber ring connects additional ANs throughout a major municipality or area, serving each AN [10].

In fact, the capacities of optical communication systems can exceed 10Tb/s be reason of a large frequency associated with the optical carrier, however, because of limitations imposed by dispersive and nonlinear effects, as well as the speed of electrical components, the data rate was restricted to 10 Gb/s or less until 1990 [11]. Channel multiplexing can be done in time or frequency, while both optical-domain techniques are commonly referred to as optical TDM (OTDM) and wavelength-division multiplexing (WDM), respectively [12]. During the early 1990s, the development of multichannel systems attracted a lot of interest, and WDM systems were commercially available by 1996 [11,13]. Since the first commercial light wave system became available in 1980, the notion of

WDM has been pursued, and the WDM was first used in 1982 to broadcast two channels in distinct transmission windows of an optical fiber in its most basic form [11, 14]. There was a lot of focus on reducing the channels pacing during the 1980s decade, however by 1990, multichannel systems with a channels pacing of less than 0.1 nm had been demonstrated [15,16]. On another hand, WDM systems were most aggressively developed throughout the 1990s [17,18]. Commercial WDM systems with a capacity of 20-40 Gb/s first debuted about 1995. But by 2000, their overall capacity had surpassed 1.6 Tb/s; many laboratories demonstrated experimentally in 2001 a system capacity of more than 10 Tb/s with transmission distances of less than 200 km, where WDM systems have reached a capacity of 30 Tb/s [19]. TDM PONs use a single wavelength providing more channels, they moderate bandwidth with reasonable cost [20]. Although WDM can support more users, it is more expensive when using multiple wavelengths in a single fiber to multiply the capacity without increasing data rates [21]. Hybrid WDM/TDM networks have positive characteristics in both schemes, and can also meet PON characteristics [22,23]. Hybrid WDM/TDM multiplexing is considered to be the technique for next-generation PON based access networks [24].

The first objective of this thesis is to investigate/simulate a performance comparison between APD and PIN photodiodes by using return-to-zero (RZ) and non-return-to-zero (NRZ) for 32 users to transmit 8Gbits/s over different transmission lengths (60 to 100Km). Second, this thesis focuses also on predictions from numerical simulation of high speed optical local area networks to transmit 10Gbps over an optimized length of 70km, showing the influence of several parameters on the transmission quality. This study has allowed us to improve the service quality and the optical communication system performance. Third, the analysis and improvement of the performance (2-10) Gbps WDM PONs using EDFA amplifiers have been simulated. We have investigated WDM PONs with a data transmission of 2 to 10 Gbps and 32 ONUs, and single EDFA amplifiers, on the basis on varying the transmission distance from 5 to 100 km to predict higher optimized values of Q-factors and lower BERs using Optisystem software. Fourth, this thesis also focuses on comparing the performances of hybrid WDM/TDM , TDM and WDM PONs with 128 ONUs, where different unidirectional passive optical networks (PONs) technologies such as wavelength division multiplexing (WDM), time-division multiplexing (TDM) and hybrid PONs operating with different users have been simulated to vary the fiber length, data rate, continuous wave laser power and number of users, aiming to enhance the performances of such networks in terms of Q-factors and bit error rates. Fifth, this thesis has analyzed the performances of WDM PON systems by using PIN and APD photodiodes where Q-factors were deduced APD and PIN receivers photodiodes were used in WDM systems with 32 users, and compared the efficiency of bit-error-rates, Finally (Sixth), this thesis analyze the performances of TDM PON system for 128 users by using RZ and NRZ modulations, and compare the most important modulation formats used in optical communications, namely NRZ and RZ.Three parameters were tested to study the performances of systems and qualities of signals, that are: Q-factors, bit error rates and eye diagrams, using the Optisystem simulation tool.

First , an introduction that consists of the research overview, problem statement, objectives, and thesis structure. **The first chapter** provides a literature review of the fiber-optics communication systems. It explains the optical transmission link and the problems that can be faced such as linear and nonlinear impairments, fiber attenuation, dispersion in optical fibers and dispersion compensation, and proposed solutions for such problems. **Chapter II** covers an overview on channel multiplexing techniques, explained in terms of fiber-to-the-home (FTTH), passive optical networks (PONs) and frequency and time division multiplexing and plesiochronous transmission hierarchy, plesiochronous digital hierarchy (PDH), Synchronous digital hierarchy (SDH) and synchronous optical network (SONET). Also, channel multiplexing techniques and basic principles with an explanation of TDM ,WDM ,CDMA and OFDM systems are discussed. After that, **Chapter III** provides some of the optical amplifiers that are utilized in optical communications. **Chapter IV** presents a summary of the appended papers [A-F] followed by references. In addition, this chapter discusses the simulation results and analysis of the proposed systems.

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CHAPTER I

Characteristics of Optical Fiber

I.1 Introduction

In 1966, Charles Kao and George Hockham of Standard Telecommunications in the United Kingdom suggested that an optical fiber might be used for communication if signal loss was less than 20dB/km. Robert Maurer, Douald Keck, and Peter Schultz worked with fused silica at Corning Glass Works, they produced a single-mode fiber with attenuation of less than 20dB/km in 1970[1].
The first optical telecommunication system was built approximately 1.5 miles under downtown Chicago in 1977, with each optical fiber holding the equivalent of 672 voice channels. Single-mode fibers with a loss of just 0.2dB/km at 1550 nm were first manufactured in 1979[2].Optical fiber cable today transports more than 80% of the world's long-distance traffic, with about 25 million kilometers of fiber deployed globally[1].
This chapter focuses on the function of optical fibers as a communication channel in lightwave systems, from section I.2 to section I.5 we utilize geometrical optics to illustrate the guiding mechanism and introduce the relevant essential concepts, section I.6 focuses on loss mechanisms in optical fibers,section I .7 discusses the origins of fiber dispersion and section I.8 goes into further depth about each specific nonlinear process ,where as section I.9 is devoted to the dispersion compensation.

I.2 Fiber Structure

An optical fiber is composed of a cylindrical silica glass core and a cladding with a lower refractive index than the core [3], the vast majority of fibers are composed of glass(silica), doping silica with GeO_2 enhances the core's refractive index. Plastic fibers can be utilized for short-distance transportation (<1km) and low-bit-rate (~Mb/s) transmission systems, they are low-cost, flexible, and simple to install and connect.Glass fibers are widely used in long-distance and high-bit-rate systems, they are used because the signals move through fibers with less loss and are therefore resistant to electromagnetic interference and sufficient capacity to transport more bits of information [1].

I.3 Ray Propagation in Fiber

Take into account a step-index fiber with a greater core index n_1 than cladding index n_2, the critical angle will be ϕ_c , where a ray with an angle $\phi \succ \phi_c$, at B, this ray experiences absolute internal reflection, as shown in Fig I,1, the reflected ray BC is subjected to absolute internal refraction once more at C , this process is referred to as frustrated total internal reflexion because it persists until the output is completed. Light is effectively transmitted from the input end to the output end of the fiber using this mechanism [3, 1].

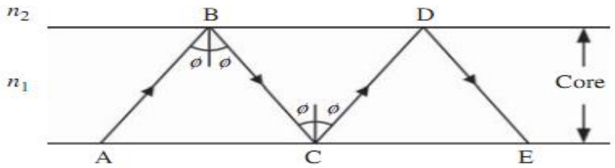


Figure I.1 Signal propagation in a fiber using the total internal reflection [1]

The coeficient of power reflection can be written as:

$$R_p = \frac{P_r}{P_i} \qquad (I.1)$$

Where *: Pr* is reflected power and *Pi* is incident power.

When the absolute internal reflection, $R_p = 1$, all of the incident ray's power is expressed in the reflected ray, it is for this reason that it is referred to as total internal reflection (TIR), refraction is often present as natural reflection occurs and $R_P \prec 1$.

I.4 Numerical Aperture (NA)

Consider a ray that makes an angle i with the fiber input (Fig I,2),we have by using Snell's law [4] :

$$\sin\ i = n_1 \sin\ \theta = n_1 \cos\ \phi \qquad (I.2)$$

Considered that the refractive index of air is one, if this ray must undergo absolute internal reflection at the core–cladding interface.

The angle θ should be greater than the critical angle ϕ_c , if this ray must undergo absolute internal reflection at the core–cladding interface.

$$\phi \succ \phi_c \qquad (I.3)$$

$$\sin\ \phi \succ \sin\ \phi_c \qquad (I.4)$$

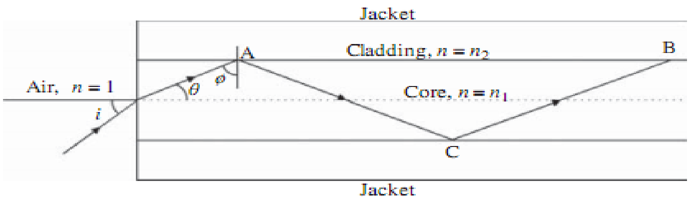


Figure I.2 The fiber's numerical aperture (NA) [1]

The numerical aperture of the fiber (NA) reflects its light-gathering capability[3],the fiber's numerical aperture (NA) is denoted as :

$$NA = \sin\ i_{\max} = (n_1^2 - n_2^2)^{1/2} \qquad (I.5)$$

And $i_{\max}$ is called the maximal acceptance angle, the relative index difference is :

$$\Delta = \frac{n_1 - n_2}{n_1} \qquad (I.6)$$

The change in fractional index at the core-cladding interface is Δ , where Δ should be as large as possible to couple as much light into the optical fiber as possible[3].

I.5 Different types of fiber

There are 2 different types of fiber: single-mode and multimode. A fiber is said to be single mode if only one optical path is possible for the light and the opposite, a fiber is called multimode if several paths are possible. multimode fibers can, in turn, be divided into :

I.5.1 Multimode fibers with index jump

In index hopping fibers (Fig I.3), a large number of light rays are propagated by total reflection.propagates by total reflection. The number of rays is a function of the angle of incidence of the light. light. The total reflection is ensured by the values of the refractive indices n_1 (core) and n_2 (sheath) with always $n_1 > n_2$.

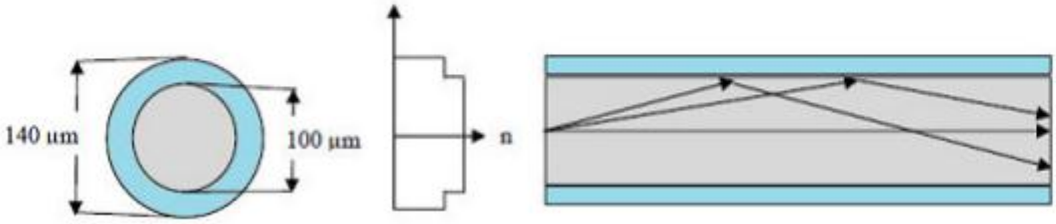


Figure 1.3 Index hopping fiber[3].

The multimode fibers with index jump are intended for short distance transmissions, they use the wavelengths distances, they use the wavelengths 850 nm and 1300 nm[3].

1.5.2 Multimode graded index fibers

In graded index fibers (Fig I.4), the core is made of successive layers of glass with a close refractive index. successive glass layers with a close refractive index. Thus, the index decreases in a continuous way continuously, from the center of the core to the core/sheath interface. We are approaching an equalization of propagation times, which means that we have reduced modal dispersion. All rays are refocused at the center of the fiber,attenuation and signal broadening are much lower than in the index hopping fiber[3].

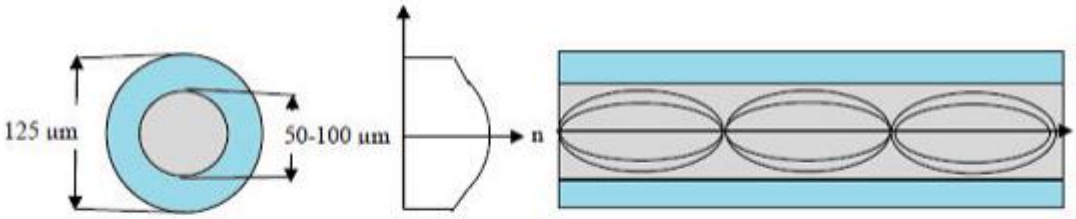


Figure I.4 Gradient index fiber[3]

Gradient index fibers are the most used for medium distances.

I.5.3 Single-mode fibers

Single mode fibers (Fig 1.5), have a very thin core, the size of a hair. The fact that the core is so thin will force the light signal to propagate in a straight line, so it does not meet the cladding and is not disturbed.The fact that the core is so thin will force the light signal to propagate in a straight line, so it does not meet the cladding and is therefore not disturbed, and consequently a modal dispersion almost zero[3].

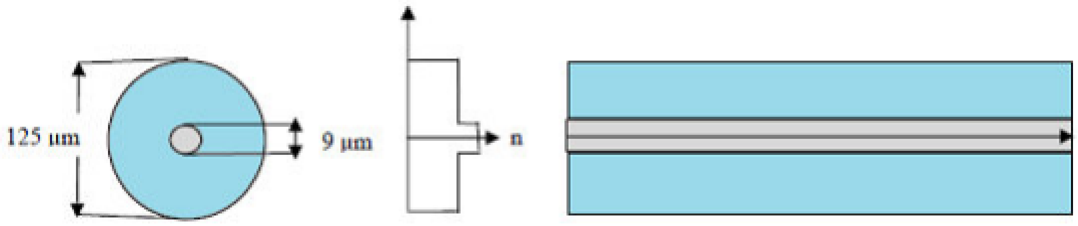


Figure I.5 Single mode fiber[3]

Single mode fibers are intended for long distance transmissions, they are used at used at the wavelength of 1550 nm have an extremely fine core diameter (8 to 10 μm in general), small compared to the diameter of the cladding (8 to 10 μm in general), small compared to the diameter of the cladding (125μm) and close to the of the wavelength of the injected light[3]

I.6 Optical Communication System

Optical fibers are widely used in fiber-optic communications, the communication system for optical fibers is just like other communication systems, the difference between them is that the optical fiber is the communication medium while the transmitter and receiver are configured to meet the specifications of the optical fiber, it is based on three key components: a transmitter, a receiver and a channel of communication as shown in the Fig I.6 [2].

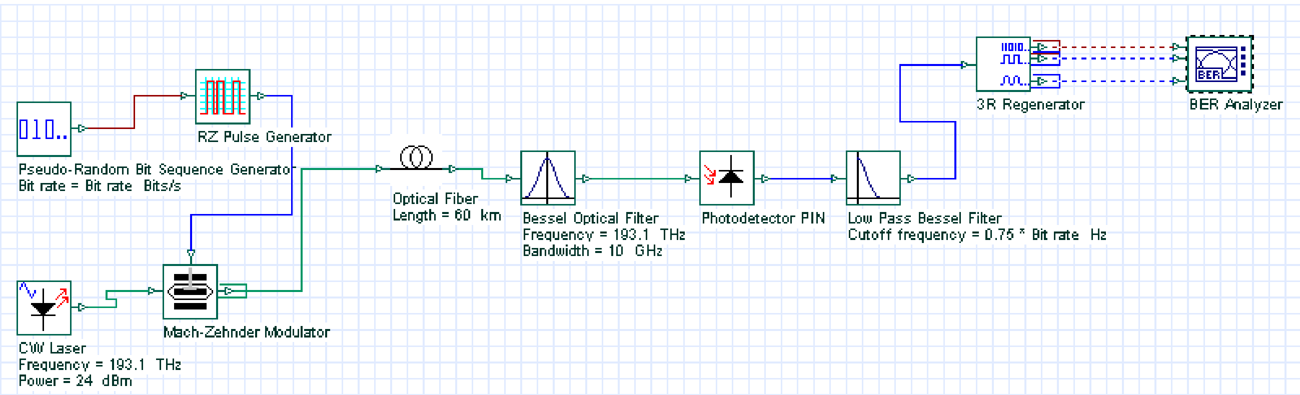


Figure I.6 Diagram of Optical Communication System

The optical communication channel's main objective is to transmit the signal without loss or distortion, with a loss (attenuation) of 0.2dB/km, the light wave may be transferred via the optical fiber,long-haul applications, on the other hand, see a 1% increase in fiber loss per 100 km,the optical fiber design must account for fiber loss ,described as a method of determining the device's location between repeaters or amplifiers [2], multi-mode fibers (MMF) are those that follow several propagation paths or transverse modes, while single-mode fibers only support a single mode fibers (SMF),multi-mode fibers are used for short-distance communication connections and have a larger core diameter, except for applications requiring a large amount of power to be transmitted,single mode fibers are used for most communication links longer than 1,000 meters [5] .

I.6.1 Emission part

I.6.1.1 Light emitting diode (LED)

We classically distinguish the light-emitting diodes (LED) and laser diodes (DL) according to the type of mechanism brought into play for the emission of light (spontaneous emission for LEDs and stimulated emission for LDs). In the case of high speed links, only the In the case of high-speed links, only laser diodes, which are much more efficient, are used.
One calls electroluminescence the emission of a luminous radiation due to an electronic excitation in a material. In the case of a light-emitting diode (LED), it is the spontaneous emission of light caused by the injection of electrons through through a particular PN junction polarized in direct (FigI.7)[6].

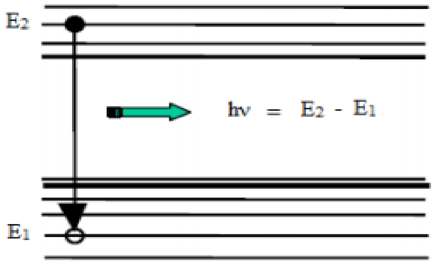


Figure I.7 Spontaneous emission process [6]

The semiconductors used to convert electrical energy into light energy are often gallium-based compounds [6]. light energy are often gallium-based compounds [6].

a) Laser Sources
A laser is a semiconductor device that generates monochromatic and coherent light monochromatic and coherent light acronym of "Light Amplifier by Stimulated Emission of Radiation ". The laser diode is based on three fundamental processes to perform the generation of the light. These processes are the absorption, the spontaneous emission and the stimulated emission (Fig I.8)[8].

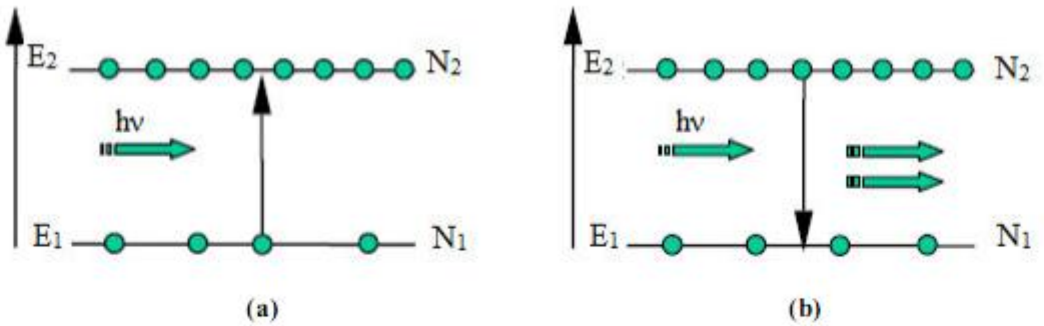


Figure I.8 Schematic of the absorption (a) and stimulated emission (b) processes [8].

To obtain the laser effect, it is necessary to privilege the stimulated emission to the detriment to the detriment of the two other processes. Two conditions must be fulfilled to favor this stimulated emission this stimulated emission and thus obtain the laser effect:

- It is necessary to have enough electrons in the higher energy state. In a semi conductor, this is achieved by an operation called electrical pumping, which consists in promoting a maximum to promote a maximum of electrons in the conduction band: This is called a population called a population inversion.
- It is necessary to promote the stimulated emission: it is therefore necessary to have enough incident photons incident photons (exciters). For this, we enclose the semiconductor in a cavity resonant cavity constituted for example by a Fabry-Perot type resonator, thus forcing thus forcing the light energy to accumulate.

b) Principle of the laser

All types of lasers (including laser diodes) have the following two elements following elements:

- An amplifying medium for the light (stimulated emission amplification).
- An optical feedback that consists in reinjecting part of the light into the amplifier

Amplifier: a laser is therefore similar to an oscillator. The optical feedback is often obtained by The optical feedback is often obtained by placing the amplifying medium in an optical cavity (Fabry-perot cavity) [4].

c) Optical feedback

The laser diode uses the optical feedback that allows to change from an amplifying behavior into an oscillator. This is obtained by placing the active medium inside a inside an optical cavity. This cavity is made of two partially reflective mirrors with reflection index reflective mirrors with reflection index R1 and R2 as shown in (Fig I.9)[4].

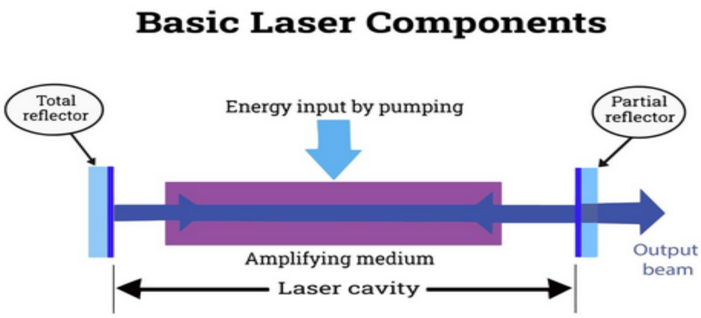


Figure I.9 Structure of a laser diode with a Fabry-Perot resonant cavity[4]

The positive feedback is determined by the reflections at the ends of the cavity. The optical wave generated inside the active zone makes as many round trips inside the cavity as it passes through the the cavity as many times as it passes through the amplifying medium.

I.6.1.2 User Defined Bit Sequence Generator

To generate the sequence of data bits to be transmitted, a pseudo random bit sequence (PRBS) is utilized to generate a RZ or NRZ electrical bit stream.

I.6.1.3 NRZ Pulse Generator: Pulse generator without zero return.

Internet data, voice data after analog-to-digital conversion (ADC), or any other type of digital data in an electrical domain can be used as the message signal. Non-return-to-zero (NRZ) and return-to-zero (RZ) are the most common pulse shapes p(t)) [1], when there are two consecutive ‘1's in a bit stream, the signal in NRZ does not return to zero, while in RZ, the signal returns to zero at the end of each bit slot [1].

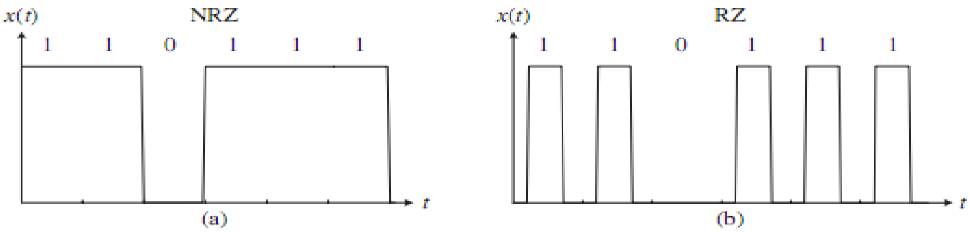


Figure I.10 Pulse shapes: (a) NRZ, and (b) RZ

As shown in Fig I.10, when compared to RZ, NRZ has the advantage of having fewer transitions between ‘0' and ‘1' since the signal amplitude stays the same if consecutive bits are ‘1' or ‘0'. As a result, an NRZ signal has a smaller bandwidth than a RZ signal [2]. The fact that the pulse frequency of a RZ pulse is shorter than that of an NRZ pulse explains the RZ signal's wider spectral width [1,2].

I.6.1.4 Optical Modulation

The first step in designing an optical system is determining how electrical data will be converted into an optical signal containing the same data.The original electrical data may be analog, but it is always converted to a digital bit stream (RZ or NRZ format) consisting of a pseudorandom sequence of 0 and 1 bits [3].Direct modulation and external modulation are two approaches.

a / Direct Modulation

fiber optic communication systems is that they can be easily modulated. easily modulated. The modulation of the current flowing through them leads directly to the intensity intensity modulation of the emitted light. This technique is called direct modulation (figureI.11) [3,7].

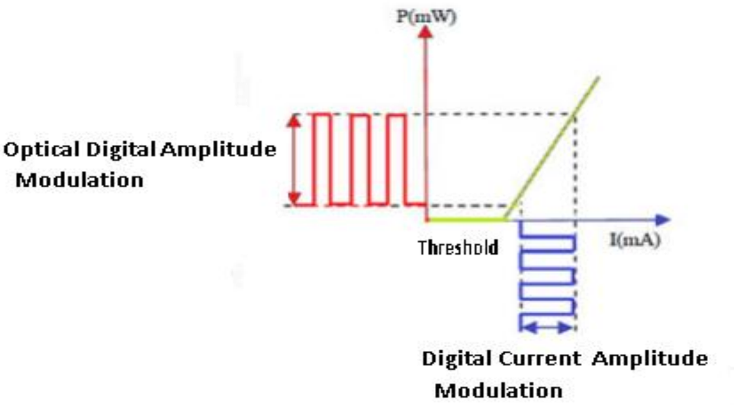


Figure I.11 Direct modulation of a laser diode [3]

This direct modulation solution requires relatively few components. Apart from the laser laser, only a current generator and a driver are needed. The first one will emit at a given given rate a sequence of data.

The role of the driver is to control the optical source at the level of the emitted powers (by fixing the values of the supply current). To do this, it modifies and transforms the levels of of the current coming from the generator.

b/ External Modulation

External modulation consists of writing the electrical data on a continuous optical signal signal. It is obtained by directly modulating the light beam at the output of the laser and not the supply current at the laser input. Thus the defects of the direct modulation modulation which are the responsibility of the laser will no longer be present on the optical signal.

This modulation consists in using an external modulator. This one is controlled by an external voltage v(t), modulated and representative of the information to be transmitted. This voltage applied to the modulator has the property to modify the transmission factor in intensity at the output. The continuous optical signal emitted by the laser supplied by a constant current is thus little degraded. By crossing the modulator, it undergoes the changes in the transmission factor and the output signal is modulated according to v(t). A driver is often present between the data and the modulator in order to fix the levels of v(t) and choose the modifications of the transmission factor [3,7].

There are two types of external modulators: Mach-Zehnder modulators and electro-absorbent modulators.

a) Mach-Zehnder Modulator

It consists of two Y junctions as shown in Fig I.12. The light injected at the input is split in two. The two beams then recombine at the output of the component. A voltage is applied to one of the two arms of the MZ [4-5]. As a result, the refractive index of the electro-optical material is modified by the application of a voltage, thus causing a phase shift between the two beams. Depending on the difference in direction (relative phase) created, the two beams are created, the two beams interfere constructively (all the optical power is available at the output), or destructively available at the output), or destructively (no light is injected into the output guide). This device is realized in integrated optics on lithium niobate (LiNbO3), semiconductors (GaAs or InP), or even polymers [2]. The application of a voltage on an electrode allows to control the phase shift induced by the electro-optical effect and to encode the electrical information in optical form. The absence of parasitic phase modulation thus avoids any transmission problem transmission problems related to the chirp[2].

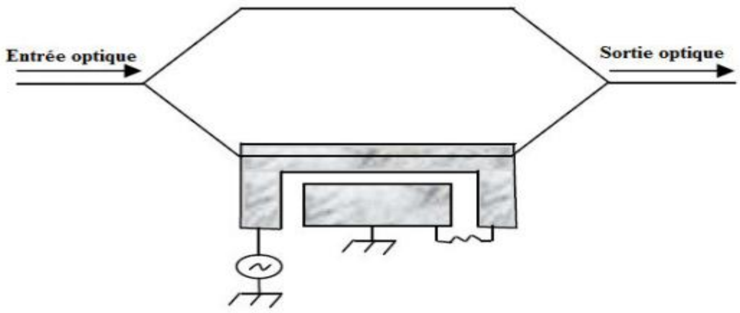


Figure I.12 Mach-Zehnder interferometer structure[2]

The insertion losses of the device come from the coupling efficiency with the fiber, the propagation losses of the guides, especially in the bends. propagation losses of the guides, especially in the bends: 4 to 6 dB is a typical value [2]. The LiNbO3 modulators have been studied since the 1980s, but their development has been slowed down by their but their development was slowed down by their specific drawbacks (sensitivity to optical polarization, current cost of 1 to 10,000). In 2003, the situation changed as they were selected as candidates for future long-distance optical transmissions at future long distance optical transmissions at 40 Gb/s, because they do not introduce chirp (widening of the emitted line due to the modulation) on the wavelength of the associated continuous laser.

b) Electroabsorbent modulator

The operating principle of electro-absorption modulators is based on the modifications of the absorption spectrum of a semiconductor submitted to an electric field. This effect is known as the the name of Franz-Keldysh effect [6] in a massive material and of confined Stark effect in a quantum material. . The derivative of the absorption with respect to the wavelength is greatest in the vicinity of the absorption edge [5]. An increase of the electric field translates the absorption edge towards wavelengths and thus increases the absorption of the light passing through the semi conductor .
the modulators currently have the same geometrical configuration as a laser diode. The guiding ribbon is buried between two confinement layers of P-type and N-type forming a polarized junction. N-type confinement layers forming an inversely polarized junction. The material of the optical guide is chosen so that the wavelength of its absorption edge is slightly lower than the wavelength of the signal whose intensity is to be intensity is to be modulated. For example, the guide will be made of undoped InGaAsP and the confinement layers in Indium Phosphide (InP) to modulate an optical

wave at 1.55 µm. At this wavelength, the guide is transparent for a zero voltage and brings an attenuation for a negative voltage.
The performance depends on the material used (massive or quantum well). The devices with the guide is formed of quantum wells make it possible to obtain an electro-absorption efficiency per unit of length length and a higher bandwidth but they require a higher control voltage and are more sensitive to voltage and are more sensitive to the polarization of the light than devices whose guide is formed of massive materials. guide is made of solid materials. Despite the sensitivity to polarization, the advantage of this structure is that it structure is to allow to associate on the same InP substrate a DFB laser diode operating in continuous and an intensity modulator.

I.6.2 Optical Receivers

The optical signal received at the output end of the optical fiber is converted back to the original electrical signal by an optical receiver, designing receivers is to receive desired efficient signals with a minimum BER, to achieve the customer's requirement,such design comprises of [6]:

I.6.2.1 Positive-intrinsic-negative (PIN) Photodiode

PIN is divided into three zones: the first is P-doped to produce a hole excess, the second has an intrinsic region known as the absorption zone, and the third is N-doped to produce an excess of electrons[9].A wider depletion region is needed to allow operation at longer wavelengths where the Light penetrates more deeply into the semiconductor material,to do this the material of type n is doped so lightly that it can be considered intrinsic, and a strongly doped layer of type n (n+) is added to make low resistance contact(Fig I.13). As can be seen in Fig I.13, this establishes a PIN structure, where all absorption takes place in the depletion region[10,11,12,13]

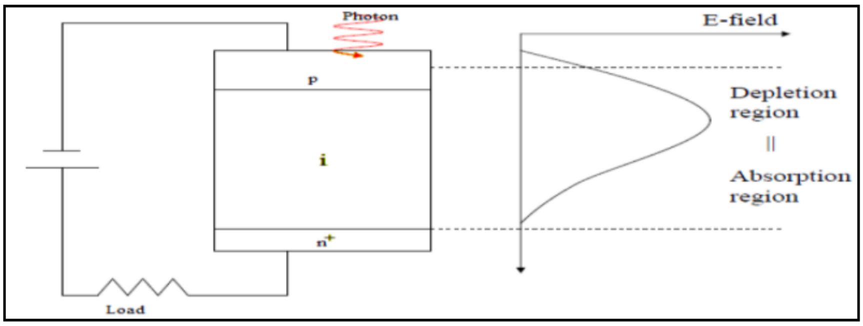


Figure I.13 PIN photodiode showing combined absorption and depletion [10].

I.5.2.2 The avalanche (APD) Photodiode

The avalanche photodiode (APD) is the second major type of optical communications detector; it has a more complex structure than the PIN photodiode and produces an extremely high region of the electrical field, as shown in Fig I.14

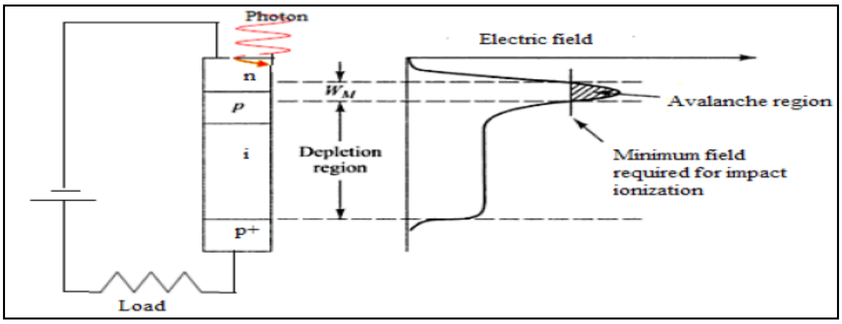


Figure I.14 Avalanche photodiode showing high electric field region [10]

The avalanche effect is exploited in a photodiode to multiply the electrons. Such an effect is used by the generation of several photoelectrons to increase the electrical signal strength. APDs are commonly used for converting optical data into electrical form in laser-based fibre optic systems, these are high-sensitivity, light sensors with high speed semiconductors[9]; it is well known that the internal gain of APDs provides higher sensitivity in Optical receivers than PIN photodiodes[14,10]), as a result, in addition to the depletion area, where most photons are absorbed and the primary carrier pairs are formed, there is a high-field region where holes and electrons can acquire sufficient energy to excite new pairs of electron-holes, this is known as impact ionization, and it is the phenomenon leading to the breakdown of avalanches in ordinary reverse diodes [11,12,13].
APD can give factors as great as 104 to the carrier multiplication. Most of the III-V semiconductors have almost identical electron and whole ionization rates, resulting in very noisy APDs made from these materials. The Si-APDs are comparatively less noisy for silicone [10,15,13].

Table I.1: differences between a PIN photodiode and APD

This table gives information about the differences between a PIN photodiode and APD to know more details about it.

PIN photodiode	APD photodiode
-PIN photodiode does not have a high-intensity electric field region. - Sensitivity is very low in PIN photodiode. - The responsibility of a PIN diode is limited. - Cost is low. - S/N ratio is very poor. - Conversion efficiency is 0.5 to 1.0 amps/watt. - The response time of PIN is half that of APD. - The detector circuit is very simple.	-APD is a high-intensity electric field region. -Sensitivity is very high in APD. -The responsibility of APD can have much larger values, -Cost is high. -S/N ratio is better. -Conversion efficiency is 0.5 to 100 Amps/watt. -The response time of APD is almost double that of the PIN, -The detector circuit is more complex.

I.6.2.3 Filter circuit

In order to minimize the noise at the output of the receiver, the digital signal must be filtered in a band $0-\Delta F$ that is as small as possible, while not creating ISI, i.e., such that the response of the filter to one symbol cancels at all decision times on neighboring symbols. According to the Nyquist criterion, we know that the rectangular low-pass filter of width $\Delta F = F_r/2$ (with Fr the frequency rate of the signal) has this property. However, this theoretical filter is not realizable. Moreover, the criterion applies to Dirac pulses, and not to pulses in NRZ format. We therefore use the "practical Nyquist filter" whose noise bandwidth, under the usual conditions, is approximately $\Delta F = 0{,}8 \times F_r$

- **3R Regenerator** making it possible to analyze/calculate the BER.
- **BER Analyzer** that displays quality (Q) factor and Bit Error Rate (BER) values.

I.7 Fiber Attenuation

Optical fiber attenuation, has proved to be one of the most critical reasons in their widespread use in telecommunications[5,4],attenuation, also known as loss of fiber, loss of transmission, and loss of power, means reducing the intensity of light or the power of light as it passes through the fiber. Fiber losses, which lower the signal power reaching the receiver, are another limiting factor [3]. Because optical receivers requirea specific minimum level of power to correctly recover the signal, fiber losses restrict the transmission distance fundamentally, only until losses were decreased to an acceptable level in the 1970s did the use of silica fibers for optical communications become viable. In the 1990s, optical amplifiers were available [3], the attenuation unit is dB/km, and the main cause of attenuation in an optical fiber is scattering and absorption [3,4],the attenuation can be expressed as the optical fiber input power and output optical power ratio after L length of optical fiber ,this ratio is a function of wavelength and can be described as[4] :

$$\alpha(dB/Km) = \frac{10}{L} Log_{10}\left(\frac{P_{out}}{P_{in}}\right) \qquad (I.7)$$

I.7.1 Absorption

Material absorption is a loss mechanism induced by the material composition and fabrication process of the fiber, in which some of the transmitted optical power is wasted as heat in the waveguide,extrinsic absorption (produced by contact with one or more of the glass's basic components) vs. intrinsic absorption (caused by impurities within the glass)[4,5].

The presence of impurities in the fiber material, such as OH ions, is the main absorption factor in fiber (water), these ions penetrate the fiber during the chemical manufacturing process or as a result of the environmental humidity[5],at 1310 nm, attenuation is 0.4dB/km, and at 1550 nm(Fig I.15), attenuation is 0.25dB/km for normal single-mode fiber, both frequencies are found in low-water peak regions[5].

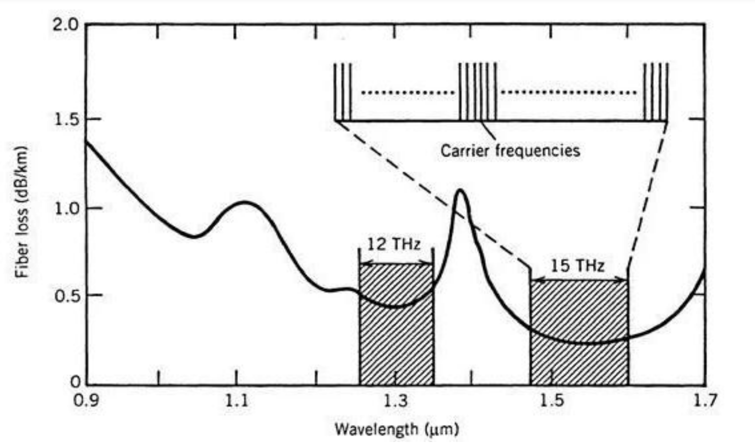


Figure I.15 Typical loss spectrum of silica fibers and low-loss transmission windows [5]

I.7.2 Rayleigh Scattering

Rayleigh scattering is a fundamental loss process induced by changes in local microscopic density.During fiber production, silica molecules migrate randomly in the molten stage before freezing in place [2,3,4].The interaction between the light wave and the fiber molecules will cause the light from the fiber waveguide to escape or reflect back to the source,this is referred to as scattering[2,3,4].

$$\alpha_{Scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 k_B T_f B_T \qquad (I.8)$$

Where (n) is the refractive index, k_B the Boltzmann's constant, p is the photoelastic coefficient, T_f is the fictive temperature, and B_T is Isothermal compressibility.

I.7.3 Intrinsic Attenuation

It is due to the assembly of two optics of different opto-geometric characteristics.

a) Different core diameters

For this manipulation, we will use a single mode fiber with a diameter of 8 µm and a multimode fiber with a diameter of 50 µm. If we assume, as a first approach, that the energy is homogeneously distributed in the fibers, the attenuation, in the direction of transmission from large core to small core, is :

$$A = 20 \log D_2 / D_1 \tag{I.9}$$

b) Different numerical openings

The experiment can be approximated relatively well by :

$$A(dB) = 0{,}1 \log(ON_1 / ON_2) \tag{I.10}$$

c)Different index profiles

If we connect a fiber with index jump with a fiber with index gradient, the loss is about 3 dB.

d)Combination of phenomena

The manufacturing tolerances of the fibers give rise to coupling losses.

I.7.4 Extrinsic Attenuation

a) Fiber eccentricity

The correspondence between theoretical and experimental curves shows that the power distribution in the fiber is uniform. The attenuation values are related to the injection conditions depending .

b) Angular deviation

The order of magnitude to remember is that an angular deviation of 1 degree can produce an attenuation of 0.5 dB.

c) Other defects of the connection

The non-perpendicularity of the faces (deviation of 2 to 3 degrees) causes an attenuation of 0.3 dB; the roughness of the faces (r = 5 µm) also gives 0.3 dB of loss. Conclusion, it is necessary that the two optical faces in contact of the connection are perfectly sawn and polished.

I.8 Dispersion in optical fibers

The dispersion of fibers is the extension of the light pulse as it passes through the fiber. This will lead the pulse to interfere with the closer pulses and consequently make it impossible to accurately recover the original signal, the effect is known as intersymbol interference (ISI). During the transmission of a signal, various forms of signal dispersion, such as chromatic dispersion and polarization-mode dispersion, may occur [5],the phenomenon is illustrated in Fig I.16

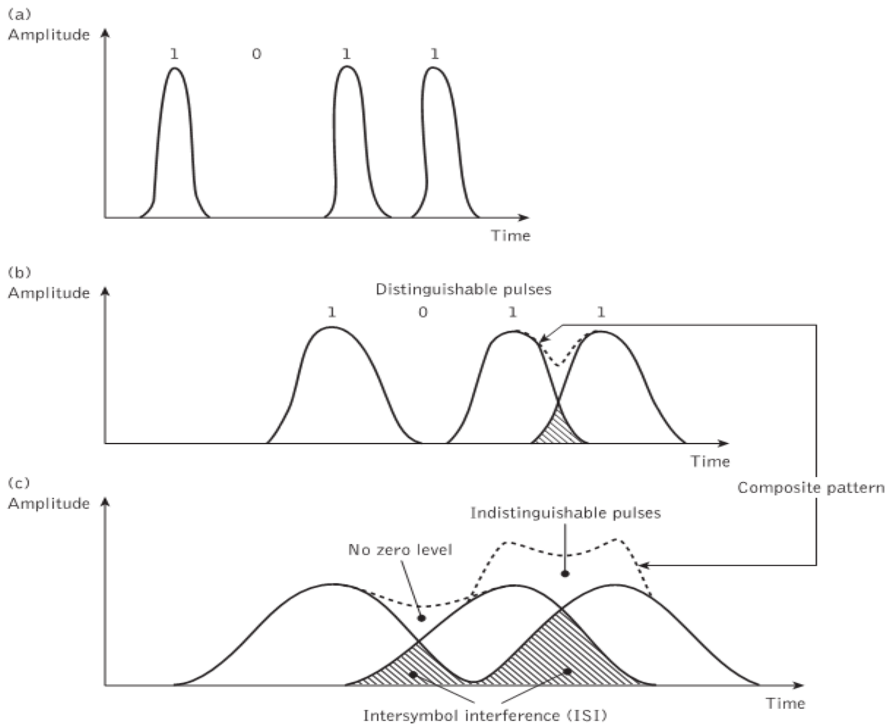


Figure I.16 An illustration using the digital bit pattern 1011 of the broadening of light pulses as they are transmitted along a fiber: (a) fiber input; (b) fiber output at a distance L1; (c) fiber output at a distance L2 > L1[5]

For no overlapping of light pulses down on an optical fiber link the digital bit rate B_T must be less than the reciprocal of the broadened (through dispersion) pulse duration (2τ)[5].
Hence:

$$B_T \leq \frac{1}{2\tau} \tag{I.11}$$

I.8.1 Chromatic Dispersion

Any phenomenon in which distinct components of the transmitted signal move at different velocities in the fiber and arrive at different times at the receiver is known as dispersion [20].Chromatic dispersion is the term given to the phenomenon by which different spectral components of a pulse travel at different velocities[20].Chromatic or intramodal dispersion can occur in any type of optical fiber and is caused by the optical source's finite spectral linewidth[5].
The pulse broadening that occurs in a single mode is chromatic dispersion. The main cause of this broadening is the optical source's finite spectral width. Chromatic dispersion is dependent on the wavelength and thus increases with the optical source spectral width [5]. It is possible to define Chromatic Dispersion as:

$$D = \frac{1}{L}\frac{d\tau_g}{d\lambda} = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right) = -\frac{2\pi c}{\lambda^2}\beta_2 \tag{I.12}$$

Where the dispersion is D, the pulse traveling distance is L, the delay difference per wavelength to propagate the distance L is $\frac{d\tau_g}{d\lambda}$, the group velocity is V_g, the GVD (Group Velocity Dispersion) parameter is β_2, the speed of light is c. Where $\beta_2 = \frac{d^2\beta}{d\omega^2}$, ω is the angular frequency, and β is the wave propagation constant is β [5,20 ,21], in the absence of chromatic dispersion, $\beta_2 = 0$, there is a so-called zero-dispersion wavelength, the chromatic dispersion is said to be normal if $\beta_2 > 0$, the chromatic dispersion is said to be anomalous if $\beta 2 < 0$, [20]. Two causes of chromatic dispersion exist: dispersion of materials and dispersion of waveguides [5,20].

I.8.1.1 Material Dispersion

Due to material dispersion ,the varying group velocities of the various spectrum components launched into the fiber from the optical source cause pulse broadening, it happens when the phase velocity of a plane wave propagating varies nonlinearly with wavelength in a dielectric medium [5], a material is said to have material dispersion, if the second differential of the refractive index with respect to wavelength is not zero (i.e. $d^2n/d\lambda^2 \neq 0$)[5].The refractive index of silica, the material used in fiber production, varies with the optical frequency ω, resulting in material dispersion [3,2]. The index of refraction of a fiber's core material is a function of wavelength [2], as the wavelength increases its variance decreases as the wavelength increases, as shown in Fig (I.17).

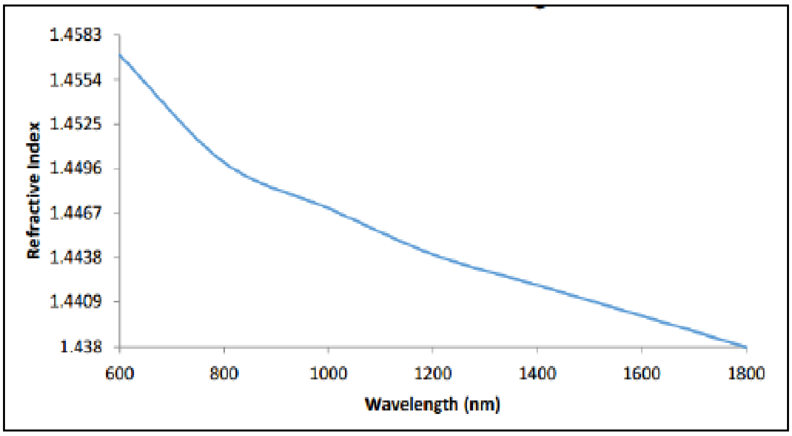


Figure I.17 Variation of Refractive Index as a Function of Wavelength [2]

Material dispersion is: $$|D_{ma}| = \frac{\lambda}{c}\left|\frac{d^2n}{d\lambda^2}\right| \quad (I.13)$$

Where the material dispersion is D_{ma} and n denotes the core's refractive index, which is often expressed in units of $psnm^{-1}km^{-1}$,the refractive index $n(\omega)$ is well approximated by the Sellmeier equation[3]

$$n^2(\omega) = 1 + \sum_{j=1}^{M} \frac{B_j\omega_j^2}{\omega_j^2 - \omega^2} \quad (I.14)$$

The resonance frequency is ω_j , and the oscillator strength is B_j, depending on whether the dispersive characteristics of the core or the cladding are examined, n stands for n_1 or n_2 [3].

I.8.1.2 Waveguide Dispersion

The diameter of the fiber core determines waveguide dispersion, which allows signals of different wavelengths to propagate at different speeds, spreading the pulse and causing it to interfere with adjacent pulses [2], dispersion in a waveguide can be described as:

$$D_{wg} = -\frac{n_1\lambda\Delta}{c}\frac{d^2b}{d\lambda^2} \quad (I.15)$$

When $d^2B/d\lambda^2 \neq 0$ A=1 ,where B is the propagation constant of a single mode , the fiber exhibits waveguide dispersion, waveguide dispersion is practically non-existent in multimode fibers, since the majority of modes propagate far from cutoff, and it is typically insignificant when compared to material dispersion ($\approx$ 0.1 to 0.2 ns km^{-1})[5].

I.8.2 Polarization Mode Dispersion (PMD)

Fiber birefringence influences the polarization state of the optical signal and induces pulse broadening, resulting in polarization mode dispersion. Fiber birefringence can be caused by a number of factors, including manufacturing defects, fiber bending or twisting, and weather conditions. Signal energy is split into two polarization modes at specific wavelengths, due to birefringence along the fiber the two polarization modes travel at different velocities. Pulse spreading would be caused by the difference in $\Delta\tau_{PMD}$ between the two polarization modes(Fig I.18) [2].

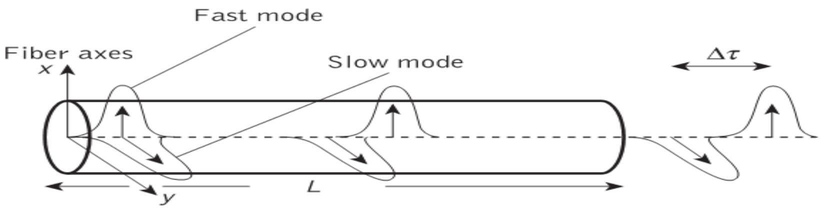


Figure I.18 Time domain effect of polarization mode dispersion in a short fiber length with a pulse being launched with equal power on the two birefringent axes, x and y, becoming two pulses at the output separated by the differential group delay [5]

$$\Delta_{PMD} = \left| \frac{L}{V_{gx}} - \frac{L}{V_{gy}} \right| \qquad (I.16)$$

Where L is the pulse's travel distance, and the group velocities are V_{gx} and V_{gy} of the two polarization modes. The polarization-mode dispersion can be measured using the following formula.

$$D_{PMD} \approx \frac{\Delta\tau_{PMD}}{\sqrt{L}} \qquad (I.17)$$

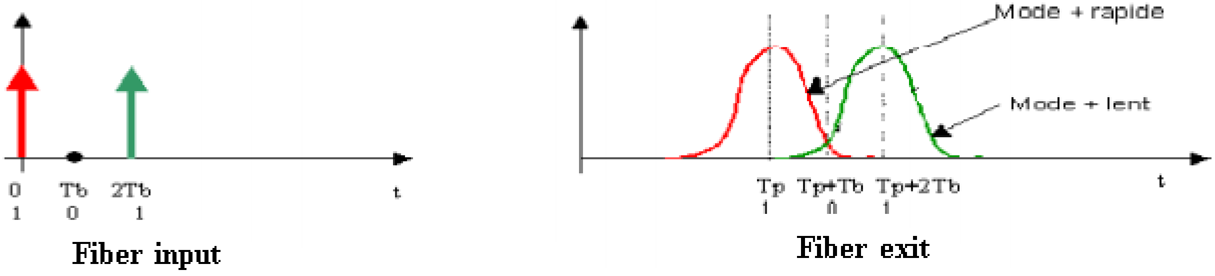
In the time domain for a short section of fiber, the differential group delay (DGD)[5]

$$\Delta\tau = \delta\tau_g L \qquad (I.18)$$

$\Delta\tau$ is defined as the group delay difference between the slow and the fast modes over the fiber lengths,it is expressed in units of picoseconds per kilometer of fiber, is referred to as the polarization mode dispersion (PMD) of the fiber, where the differential group delay per unit length is $\delta\tau_g$ [5].

I.8.3 Modal dispersion

It exists in multimode fibers with index jump. Indeed in a multimode fiber fiber, several paths are possible for the light, these paths have different lengths The modal dispersion comes from the difference in the time of travel of light in the fiber depending on the path.The modal dispersion comes from the difference of the travel time of the light in the fiber according to the travelled paths(Fig I.19)[5].



FigureI.19.Modal dispersion at the exit of the optical fiber[5]

I.9 Nonlinear Processes in Optical Fibers

The assumption in fundamental fiber transmission connection design is that an optical fiber works as a linear medium, this implies that the fiber's characteristics are unaffected by optical signal power, the wavelength of the optical signal remains constant as it propagates through the fiber, and the signal does not interact with other signals in the fiber, for low signal power levels (approximately less than +3 dBm) this assumption is true [22]. However, the fiber exhibits nonlinear properties for high optical powers, the characteristics of the fiber are altered by high optical signal power, which consequently influences the signal, the propagating optical signal changes and loses signal strength linearly as a result of this interaction [22,23].

Several nonlinear phenomena exist, which induce excessive attenuation in the case of scattering, generally at high optical power levels[5].both nonlinear scattering processes and nonlinear power dependence of the fiber refractive index are the two basic types of nonlinear processes that occur in optical fibers, stimulated Brillouin Scattering (SBS) and stimulated Raman Scattering (SRS) are nonlinear processes that belong to the first group, both of which are usually only observed at high optical power densities in long single-mode fibers[5,14,20], these scattering processes do provide optical gain, but with a frequency shift[5].

The second group includes the Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), and Four-Wave Mixing (FWM) processes [24]. From a practical view point, the power distribution among numerous spectral lines corresponding to separate propagating waves is primarily affected by SBS, SRS, and FWM, SPM and XPM, on the other hand, primarily impact the spectral characteristics of propagating signals [24,23].

Several essential characteristics of optical fibers are provided here to look at the first nonlinear processes that occur in fibers and play a significant role within the style and development of high-power fiber laser and fiber amplifier systems, contemplate the supposed effective length (Leff), that is decided by the fiber's absorption properties.

$$L_{eff} = \frac{1}{P_0}\int P(z)dz = \int \exp(-\mu z)dz = \frac{1-\exp(-\mu L)}{\mu} \qquad \text{(I.19)}$$

P_0 I denotes the original optical power entering the fiber, the optical power inside that fiber at a particular point z along the fiber length is *P(z)*, where L is the total fiber length, and the fiber absorption coefficient at the light propagation wavelength is μ [24].

The effective area A_{eff} is another essential fiber parameter, which is defined as

$$A_{eff} = \frac{(\int_0^\infty |E_a(r)|^2 rdr)^2}{\int_0^\infty |E_a(r)|^4 rdr} \qquad \text{(I.20)}$$

Where E_a denotes the amplitude of the fundamental fiber mode and the intensity of the fiber fundamental mode at radius *r* from the axis of the fiber is $|E_a(r)|^2 = I(r)$.Furthermore, the power dependence of the glass refractive index, which is necessary to understand optical nonlinearities in fibers. The refractive index of glass can be stated as follows:

$$n = n_0 + n_2 \frac{P}{A_{eff}} \qquad \text{(I.21)}$$

Where the fiber core's linear refractive index is n_0 (measured at low optical power levels), the nonlinear refractive index coefficient is n_2 (which is $2.35\times10^{-20} m^2/W$ for silica), and the propagating light wave's optical power in watts is P.

I.9.1 Self -Phase Modulation (SPM)

When large optical energies travel through a fiber, a nonlinear medium is produced, resulting in both cross-phase modulation (XPM) (Kerr effect) and self-phase modulation (SPM)[22], in SPM,the nonlinear refractive index produces a phase shift in the propagating pulse's optical wavelength, which is proportionate to its own optical intensity, where the optical Kerr effect plays central role in the SPM phenomenon, as a result, the peak of the pulse has a different phase condition than the rising and falling edges. [24,22,21,23],

$$\Delta\Phi_{SPM} = \gamma P_0 L_{eff} \qquad \text{(I.22)}$$

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \qquad \text{(I.23)}$$

Where $\Delta\Phi_{SPM}$ denotes phase a shift of the optical signal after propagating a distance, the nonlinear coefficient is γ $(Wm)^{-1,}$ input signal power is P_0, L_{eff} denotes fiber's effective length, and the signal wavelength is L, knowing that i the derivative of phase shift with respect to time is phase shift, Eq. (I.22) may be written as Eq (I.24).

$$\Delta\omega = -\frac{d\Delta\Phi_{SPM}}{dt} = -\gamma \frac{dP}{dt} L_{eff} \qquad \text{(I.24)}$$

Where $\Delta\omega$ denotes the change in frequency caused by the change in phase shift at location L, s^{-1}
The relationship between frequency shift around the carrier frequency and the change in signal power is shown in Eq (I.24) (see Fig I.20).The leading edge of an optical pulse's amplitude causes the refractive index of the fiber to increase as it propagates through a fiber, resulting in a shift to a lower frequency for the pulse's beginning. The refractive index decreases as the amplitude of the pulse decreases, resulting in a shift to a higher frequency for the pulse's end [22]. When various optical frequencies travel at different speeds in a fiber the pulse width increases or contracts. Intersymbol interference and the worst BER result from pulse width expansion [22], further information on the propagation of chirped pulses the frequency change of the pulse is a modulation generated by a phase shift created by the pulse itself; hence the effect is known as self-phase modulation. The maximum transmission rate achievable in the fiber is limited by this phenomenon produced by high optical power [22].

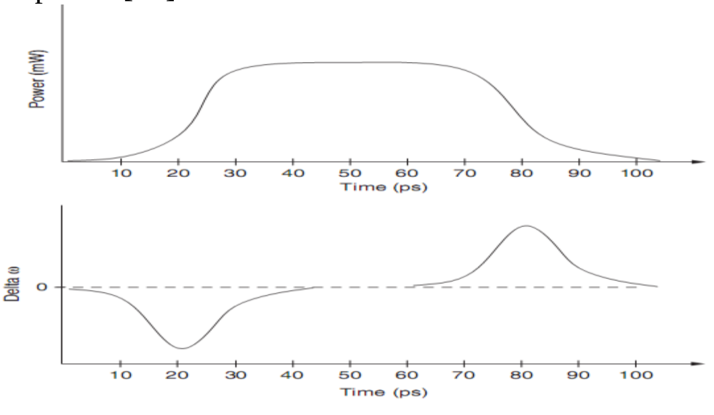


Figure I.20 Pulse frequency change due to SPM [22].

I.9.2 Cross-Phase Modulation (XPM)

XPM is the same basic phenomenon as refractive index dependency on signal strength, except that the optical power generating the effect comes from all other optical signals travelling in the fiber, not just the initial signal. Multichannel WDM, DWDM, and CWDM systems are all affected by this[22]. XPM effect is dependent on [22]

- The power of the input channel (the higher the power the greater XPM).
- Channel spacing (the greater the channel spacing the lesser the XPM).
- Fiber dispersion.
- The effective area of the fiber core (the larger the area the lesser the XPM).

In copropagating signals, XPM operates as noise, causing amplitude and jitter fluctuations. The frequency shift caused by intensity variations in another channel is given by [21]

$$\Delta B = 2\gamma L_e \frac{dP}{dt} \tag{I.25}$$

Where: dP /dt denotes the time derivative of the power in the interfering pulse,
γ = nonlinear coefficient, $(Wm)^{-1}$
This factor of 2 arises from the counting of terms in the expansion of the nonlinear polarization [21]

I .9.3 Four-Wave Mixing (FWM)

Mixing of signals can happen when two or more optical signals with differing center frequency (different DWDM channels) propagate through a fiber, resulting in the creation of additional interfering optical signal components. It's worth noting that the formula $\lambda = c / f$ =may be used to convert optical frequency to wavelength, this effect is independent of transmission rate and happens in DWDM connections with large signal strengths [22]. The Kerr effect is caused by the refractive index of the fiber being dependent on the signal strength, resulting in a nonlinear medium of transmission and creating conditions for signal mixing [22]. Summing the positive or negative integer multiples Ni of all the contributing signal center frequencies yields the center frequencies of the newly created signal components. This mixing phenomenon is related to radio frequency mixing, which is referred to as intermodulation products. [22].

$$f_{IM} = N_1 f_1 + N_2 f_2 + N_3 f_3 ... \tag{I.26}$$

$$IM_{order} = \sum_{1}^{M} |N_i| \tag{I.27}$$

Where f_{IM} = generated signal component center frequency, THz
fi = DWDM signal center frequency where i = 1 to M, THz
Ni = any integer with + or − coefficients including zer
Where i = 1 to M
M = total number of DWDM signals in the fiber

IM = intermodulation order

FWM results in two detrimental effects on the transmission performance:

- Generation of FWM components that interfere with the original signal and other DWDM signals causing interchannel crosstalk interference, which increases BER and reduces OSNR.
- To a lesser extent optical power transferred from the original DWDM signal to the generated interfering components.

The one way to decrease FWM effects (ITU-T G.652) is by using transmission fiber with a high chromatic dispersion coefficient at the signal wavelength, such as standard single-mode fiber SSM, 18 ps/nm km @1550 nm is the average chromatic dispersion coefficient of SSMF , which helps to considerably minimize FWM[22], even a reduced chromatic dispersion coefficient, such as NZ-DSF fiber, helps to reduce FWM (ITU-T G.655), this fiber has a low chromatic dispersion coefficient (4 ps/nm km @ 1550 nm) for longer transmission distances while yet being high enough to prevent FWM effects[22]. Lower signal power in the fiber is another method to reduce these effects is to [22].

I.9.4 Stimulated Raman Scattering (SRS)

Raman scattering is an important and interesting phenomena that was discovered separately in crystals and liquids in Russia (by Landsberg and Mandelstam) and India (by Raman and Krishnan) in 1928. Sir C.V.Raman, an Indian scientist who discovered this significant liquids discovery, is the process's historical name [24]. SRS causes power to be transferred from lower-wavelength channels to higher-wavelength channels when two or more signals of different wavelengths are injected into a fiber [20]. The energy of a photon at a wavelength λ is given by *hc/λ*, where Planck's constant (6.63×10^{-34} Js) is h .Thus, a photon of lower wavelength has a higher energy.The transfer of energy from a signal of lower wavelength to a signal of higher wavelength corresponds to emission of photons of lower energy caused by photons of higher energy(Fig I.21) [20].

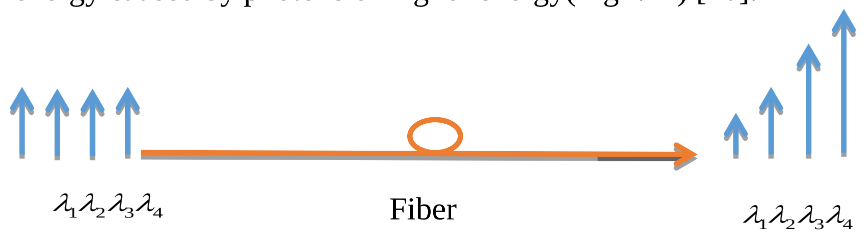


Figure I.21 The effect of SRS.Power from lower-wavelength channels is transferred to the higher-wavelength channels.

Raman scattering is based the intrinsic vibrations of molecules with the interaction of an incident light wave. When a light wave travels through a medium , it scatters creating a phonon through excitation of the molecule vibrations[24]. SRS can happens in both the forward and backward directions in an optical fiber [5]. As a result, it is clear that nonlinear scattering losses may be avoided by using an appropriate optical signal level (i.e. working below the threshold optical powers)[5].The following Eq can be used to calculate the SRS's threshold peak power in silica fiber [24]:

$$g_R \frac{P_{thpeak}}{A_{eff}} L_{eff} = 16 \quad \text{when} \quad t_p \gg 1.3\,ps \qquad (I.28)$$

Wher the stimulated scattering gain in cm/W is g, P_{thpeak} denotes the scattering process's threshold peak power in watts, and the effective length of the fiber L_{eff} is measured in centimeters, the effective area of the fiber core A_{eff} is measured in cm^2, and t_p is the propagating optical pulse width is measured in seconds [24].

$$g_R \frac{P_{thpeak}}{A_{eff}} L_{eff} = \frac{(8+\Gamma_R t_P)^2}{2\Gamma_R t_P} \quad \text{when} \quad t_P \ll 1.3\text{ps} \ , \ \Gamma_R = 6\times10^{12}\text{Hz} \qquad (I.29)$$

Γ denotes the spectral line-width of spontaneous scattering process given in hertz. Shortening fiber length, increasing fiber core diameter, and increasing the spectral line-width of the propagating laser signal all result in a higher SRS threshold [24]. SBS and SRS are seldom seen in multimode fibers due to their relatively large core diameters, which result in extremely high threshold optical power levels [5]. For SRS P_R the threshold optical power in a long single-mode fiber is given by:

$$P_R = 5.9\times10^{-2} d\lambda\alpha_{dB} \text{ Watts} \quad (I.30)$$

Where d is the fiber core diameter and λ is the operating wavelength, both measured in micrometers, α_{dB} denotes the fiber attenuation in decibels per kilometer, if lowest nonlinear performance in terms of FWM and SRS is the only goal, it's ideal to have a fiber with the highest possible A_{eff}, and D. In this case, SSMF with a D = 17 ps/nm.km and A_{eff} = 80 μm^2 at 1550 nm would be the best choice among commercially [23].

I.9.5 Stimulated Brillouin Scattering (SBS)

The Brillouin scattering phenomena is extremely similar to Raman scattering in terms of physical nature. Brillouin scattering, on the other hand, is a process in which an incident (or propagating) light wave interacts with the medium's coustical phonons (i.e., with its lattice vibration modes), SBS (stimulated Brillouin scattering) may be regarded as the modulation of light through thermal molecular vibrations within the fiber[5]. Mandelstamin1918 (published in 1926) and Brillouin (1922) anticipated this mechanism [24], it explains the inelastic scattering of a thermally stimulated acoustical wave/phonon by an incident optical wave. Brillouin is the historical term for the effect [24]. The effect of SRS (stimulated Raman scattering) is to generate scattered light of slightly lower energy, or longer wavelength [23].

The scattered light appears as upper and lower sidebands which are separated from the incident light using the modulation frequency. In this scattering process the incident photon produces a phonon of acoustic frequency [5], where the phonon is a quantum of an elastic wave in a crystal lattice. the quantized unit of the phonon has energy *hf* joules when the elastic wave has a frequency *f*, , where Planck's constant is *h*[5],as well as a photon that is dispersed because the frequency of the sound wave changes with acoustic wavelength, this results in an optical frequency shift that varies with scattering angle., the frequency shift is greatest in the backward direction, where in the forward direction, it is smallest[5]. SBS does not cause any interaction between different wavelengths, as long as the wavelength spacing is much greater than100 MHz [20].The energy of vibration modes of the lattice, which belong to the medium of light propagation, corresponds to the brillouin scattering frequency shift that occurs in the brillouin scattering spectra and may be represented as [24]:
Brillouin scattering shifts are much smaller than that of Raman scattering in the backward direction [24].

$$h\nu_B = h\frac{2nV_a}{\lambda_P}\sqrt{\left(\frac{1-\cos\theta_B}{2}\right)} \quad (I.31)$$

Where the refractive index of the medium at pump wavelength is *n*, V_a denotes the medium's acoustic velocity, and the angle between the scattered wave vector and the initial pump wave vector is θ_B, the frequency shift is around 11.25 GHz at a 1.5-μm pump light wavelength for silica fiber, which corresponds to the energy of the acoustic vibration mode in silica. V_B is inversely proportional to λ_P k. the following formulas can be used to calculate the SBS power threshold for both stationary (long-pulse) and nonstationary (short-pulse excitation) optical pulse excitation:

$$g_B\frac{P_{thpeak}}{A_{eff}}L_{eff} = 21 \quad \text{when} \quad t_p \gg 100ns \quad (I.32)$$

$$g_B\frac{P_{thpeak}}{A_{eff}}L_{eff} = \frac{(\frac{21}{2}+\Gamma_B t_P)^2}{2\Gamma_R t_P} \quad \text{when} \quad t_P \ll 100\text{ns} \;,\; \Gamma_R = 100\times10^6\text{Hz} \quad (I.33)$$

And M = 21 for the SBS process in silica fibers.
P_B is The threshold power , it is given by[5] :

$$P_B = 4.4\times10^{-3} d^2\lambda^2\alpha_{dB}\nu \text{ Watts} \quad (I.34)$$

Where d denotes the fiber core diameter in micrometers and λ denotes the operating wavelength in micrometers, the fiber attenuation in decibels per kilometer is α_{dB}, and v denotes the source bandwidth (i.e. injection laser) in gigahertz, the formula in Eq enables the threshold optical power that must be launched into a single-mode optical fiber before SBS occurs [5].

I.9.6 Optical Kerr Effects

SRS and SBS are based on the optical Kerr effect in fibers, the process of instantaneous nonlinear optical response of the dielectric medium to propagating light is devoted to this fundamental optical phenomena, this process explains a change in the refractive index of the medium due to the propagating light [24].The optical kerr effect has a simple formula that is as follows:

$$\Delta n = n_2 I \equiv n_2 \frac{P}{A_{eff}} \tag{I.35}$$

Where n_2 denotes the nonlinear refractive index of the optical medium through which high-intensity light travels, given in cm^2/W, and I denotes the light beam's intensity, expressed in W/cm^2, and the propagating beam's optical power is P, expressed in watts. The nonlinear refractive index of glass fibers has a wide range of values depending on the fiber glass composition; the range is 2-5×$10^{-16} cm^2/W$.

I.10 Dispersion Compensation

The fiber-loss problem is solved by Optical amplifiers but worsen the dispersion problem by collecting dispersive effects along the whole chain of amplifiers. An appropriate dispersion-compensation system can be used to control the dispersion problem in practice [3].

I.10.1 Dispersion Compensation Fiber (DCF)

Optical filters use to transfer function has the form $H(\omega) = H_f^*(L,\omega)$, are not easy to design. The good solution is to use an especially designed fiber as an optical filter [3], a special kind of fiber, known as the dispersion-compensating fiber (DCF), was developed during the 1990s for Dispersion-Compensating Fibers[3,25], even when nonlinear effects are not negligible, such a technique works effectively as long as the average optical power launched into the fiber connection is correctly optimized(Fig I.22)[3].

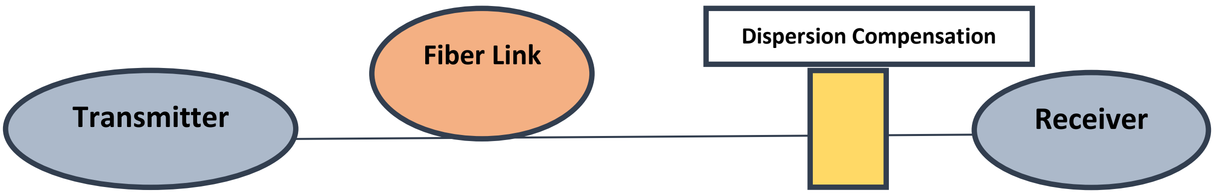


Figure I.22 Schematic of a dispersion-compensation scheme in which an optical filter is placed before the receiver [3].

The z-dependent phase factor obtained by spectral components of the pulse during propagation inside the fiber causes dispersion-induced deterioration of the optical signal. Fiber may be thought of as an optical filter with a transfer function.

$$H_f(z,\omega) = \exp(iB_2\omega^2 z/2 + iB_3\omega^3 z/6) \tag{I.36}$$

Optical "filters" with the transfer function $H(\omega)$ designed to cancel the phase factor associated with the fiber are used in all optical-domain dispersion-management methods, the output signal may be restored to its input form at the end of a fiber connection of length L if $H(\omega) = H_f^*(L,\omega)$. Furthermore, a filter like this can be used at the transmitter, receiver , or anyplace along the fiber network if nonlinear effects are negligible [3].The optical bit stream is assumed to propagate over two fiber segments with lengths of L and L_2, the second of which is the DCF. A transfer function of the kind provided in Eq I.38 exists for each fiber. The optical field is given by after passing through the two fibers [3].

$$A(L,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}(0,\omega) H_{f1}(L_1,\omega) H_{f2}(L_2,\omega)\exp(-i\omega t)\,d\omega \qquad (I.37)$$

Where the total length is $L = L_1 + L_2$, and $\tilde{A}(0,\omega)$ denotes the Fourier transform of $A(0,t)$ .The pulse will entirely restore its original form at the end of DCF if the DCF is constructed so that the product of the two transfer functions is 1. If B_{2j} and B_{3j} are the group-velocity dispersion (GVD) and third-order dispersion (TOD) parameters for the two fiber segments (j = 1, 2), the conditions for perfect dispersion compensation are

$$B_{21}L_1 + B_{22}L_2 = 0, \qquad B_{31}L_1 + B_{32}L_2 = 0 \qquad (I.38)$$

Perfect condition for dispersion compensation beside DCF can be given as [25]:

$$B_{SMF}L_{SMF} + B_{DCF}L_{DCF} = 0 \quad \text{or} \quad D_{SMF}L_{SMF} + D_{DCF}L_{DCF} = 0 \qquad (I.39)$$

And

$$D = -\frac{2\pi.c}{\lambda^2}B \qquad (I.40)$$

Where c denotes the light speed and λ is the wavelength of the pulse signal. Because in the case of SMF, D_{SMF} >0, Eq. (I.41) reveals that for dispersion correction, the dispersion coefficient D_{DCF} (in ps/nm.km) of DCF (at a given wavelength in nm) must be negative, and the length L_{DCF} (in km) of DCF must be satisfied as[25].

$$L_{DCF} = -L_{SMF}\left(\frac{D_{SMF}}{D_{DCF}}\right) \qquad (I.41)$$

I.10.2 Fiber Bragg Grating (FBG)

Because of their comparatively lengthy lengths, DCFs suffer from high insertion losses. In a log-haul system, they also increase the impact of nonlinear effects. The use of fiber-based Bragg gratings for dispersion correction can solve both of these problems to a significant extent [3]. Because of the existence of a stop band a FBG acts as an optical filter, the frequency region in which most of the incident light is reflected back, the stop band is centered at the Bragg wavelength λ_B [2]. The refractive index (RI) of the core of a fiber Bragg grating varies in a periodical manner over the length of the grating. The grating functions as an optical filter as a result of this characteristic [3,26 ,25] , FBG acts as a low-cost filter for wavelength selection and it is used for reducing chromatic dispersion [27,26,28].

Although similar gratings for dispersion correction were proposed in the 1980s, it wasn't until the 1990s that manufacturing technology progressed to the point that they could be used [3], produces a stop band in the shape of a spectral area over which the majority of incoming light is reflected back. The grating period Λ is linked to the Bragg wavelength (reflected wavelength) λ_B (see Fig I .23) by the equation $\lambda_B = 2\tilde{n}\Lambda$, where $\tilde{n}$ denotes the average mode index. When light of various wavelengths is sent into an FBG, one wavelength in particular infests the grating period and is reflected back to the input end. Because they do not interfere with the grating period, all other wavelengths pass through the fiber. As a result, FBG reflects one wavelength while transmitting all others [29,28,25,30]. In the waveguide grating, each wavelength of light travels a different distance. The constantly shifting time throughout the grating length causes this effect. Each wavelength component will enter the waveguide grating and be reflected at the place when the local grating period and the wavelength of light are matched [29,28,25,30].

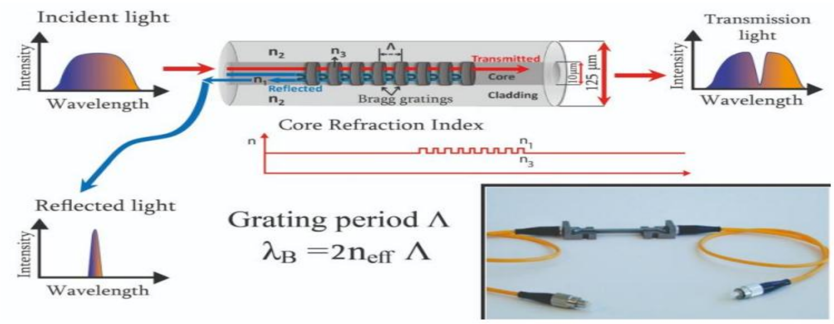


Figure I.23 Spectral response of FBG [30]

The refractive index varies along the grating length in a periodic fashion in the simplest type of grating as [3]:

$$n(z) = \tilde{n} + n_g \cos(2\pi z / \Lambda) \quad \text{(I.42)}$$

Where $\tilde{n}$ the average refractive index value and ng is denotes the modulation depth. For fiber gratings intended to function around the 1550-nm spectral area, $n_g \sim 10^{-4}$ and $\Lambda \sim 0.5\mu m$ are typical values. Two coupled-mode equations that explain the coupling between the backward and forward-propagating waves at a particular frequency $\omega = 2\pi c / \lambda$ are used to analyze Bragg gratings. These equations take the following form [3]:

$$dA_f / dz = i\delta A_f + i\kappa A_b \quad \text{(I.43)}$$

$$dA_b / dz = -i\delta A_b - i\kappa A_f \quad \text{(I.44)}$$

Where the field amplitudes of the two waves are A_f and A_b and

$$\delta = \frac{2\pi \tilde{n}}{\lambda} - \frac{2\pi}{\lambda_B}, \qquad \kappa = \frac{\pi n_g \Gamma}{\lambda_B} \quad \text{(I.45)}$$

δ represents detuning from the bragg wavelength, κ denotes the coupling coefficient, and Γ denotes the confinement factor, the coupled-mode equations may be solved analytically because of their linear character. When the optical frequency is near to the Bragg wavelength, the majority of the input light is reflected. The grating's transfer function as a reflecting filter is discovered to be[3] :

$$H(\omega) = \frac{A_b(0)}{A_f(0)} = \frac{i\kappa \sin(qL_g)}{q\cos(qL_g) - i\delta \sin(qL_g)} \quad \text{(I.46)}$$

Where $q^2 = \delta^2 - \kappa^2$ and L_g are the grating length, q becomes imaginary, and most of the light is reflected back by the grating (reflectivity becomes nearly 100% for $\kappa L_g \succ 3$) when incident wavelength falls in the region $-\kappa \prec \delta \prec \kappa$. This region constitutes the stop band of the grating. The dispersion characteristics of the grating are related to the frequency dependence of the phase of $H(\omega)$, the dispersion parameters of a fiber grating are given by [3]

$$B_2^g = -\frac{\text{sgn}(\delta)\kappa^2 / v_g^2}{(\delta^2 - \kappa^2)^{3/2}}, \qquad B_3^g = \frac{3|\delta|\kappa^2 / v_g^3}{(\delta^2 - \kappa^2)^{5/2}} \qquad (I.47)$$

The group velocity is denoted by v_g. On the high-frequency or "blue" side of the stop band, when δ is positive and the carrier frequency exceeds the Bragg frequency, grating dispersion is anomalous ($B_2^g \prec 0$). In contrast, dispersion becomes normal $B_2^g \succ 0$ on the low-frequency or "red" side of the stop band, the red side can be used for compensating the dispersion of standard fibers near 1.55µm ($B_2 \approx -21ps^2/km$)[3].a single 2-cm-long grating can compensate dispersion accumulated over 100 km of fiber.

I.10.3 Chirped Fiber Bragg Grating (CFBG)

Chirped fiber gratings, were first proposed for dispersion compensation in 1987, which feature a wide stop band, [2]. The dispersion effects are optimized with chirped FBG[31].In a chirped grating, the optical period n is not constant but changes over its length, because the bragg wavelength ($\lambda_B = 2\tilde{n}\Lambda$) changes with the length of the grating[2], depending on where the bragg condition is satisfied locally, different frequency components of an incident optical pulse are reflected at different places. The stop band of a chirped fiber grating is composed of several mini stop bands that are overlaid and changed when the Bragg wavelength moves along the grating. The stop band that results might be as wide as a few nanometers [2].The basic principle of chirped Fiber Bragg Grating is presented in Fig (I.24). It Consists a single-mode fiber having modulated core of refractive index, which has been divided by grating the plane with chirped spaces that create chirped fiber bragg grating as shown in Fig(I.24)[32].

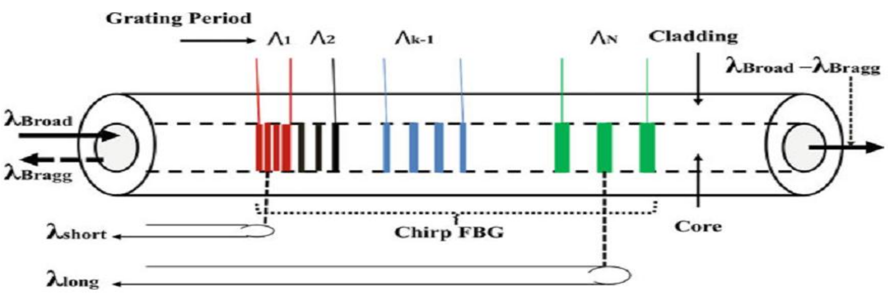


Figure I.24 Configuration of a chirped fiber Bragg grating used as a dispersion compensator [32]

Furthermore, the wavelength difference between the two split ends of the grating planes may be calculated as follows [32]:

$$\Delta\lambda = 2.n_{eff}.(\Lambda_{long} - \Lambda_{short}) \qquad (I.48)$$

Where n_{eff} *is* the effective refractive index in core and Λ is the grating period of the fiber, the time delay (τ) of different reflected wavelengths can be calculated as given by

$$(\tau_\lambda) = (\lambda_{Bragg} - \lambda).\frac{2.n_{eff}}{\Delta\lambda.c}.l \qquad (I.49)$$

Where c and *L* are speeds of light signal in vacuum and length of grating, respectively. D_g denotes dispersion of chirped fiber Bragg grating, (D_g) can be calculated as given by.

$$D_g = \frac{2.n_{eff}}{\Delta\lambda.c}.l \qquad (I.50)$$

I.11 Conclusion

This optics section gives a short introduction to optical fiber and some of the optical components used in this research ,we studied Optical fiber attenuation, also known as loss of fiber, loss of transmission, and loss of power, means reducing the intensity of light or the power of light as it passes through the fiber, and the main cause of attenuation in an optical fiber is scattering and absorption, material absorption is a loss mechanism caused by the fiber's material composition and fabrication process, extrinsic absorption (induced by contact with one or more of the primary components of the glass) or intrinsic absorption (caused by impurities within the glass), we also have dispersion in optical fibers, it is the extension of the light pulse as it passes through the fiber, this will lead the pulse to interfere with the closer pulses and consequently make it impossible to accurately recover the original signal , the effect is known as intersymbol interference (ISI), various forms of signal dispersion, such as chromatic dispersion, where it is the term given to the phenomenon by which different spectral components of a pulse travel at different velocities.where we studied a special kind of fiber, known as the dispersion-compensating fiber (DCF), was developed for dispersion compensating fibers, DCFs suffer from high insertion losses. In a log-haul system, they also increase the impact of nonlinear effects. The use of fiber-based Bragg gratings for dispersion correction can solve both of these problems to a significant extent.Fiber Bragg gratings (FBGs) are among the most important components used to reduce dispersion, FBGs are simple, and have low-cost filter for wavelength selection, low insertion loss and customized reflection spectrum, and wide bandwidth.

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CHAPTER II

Channel Multiplexing Techniques

II .1 Introduction

Optical fibers have the upside of high data transfer capacity (bandwidth), low loss, and low noise [1,2]. Contrasted with the coaxial link plant, which normally requires many fell RF intensifiers, fiber plants are when all is said in done a lot of cleaner and require almost no support [2]. Concentrates for OLANs began during the 1980s [3,2]. Fiber get to frameworks are likewise alluded to as fiber-to-the-x (FTTx) framework, where x can be home, curb or building and so forth[4,2], contingent upon how somewhere down in the field fiber is sent or that it is so near the client [5,2]. In a fiber-to-the-home (FTTH) framework, fiber is associated right from the specialist organization to family clients [6,2]. In a FTTC framework, fiber is associated with the control of a network where the optical sign is changed over into the electrical area and conveyed to end clients through bent sets (Fig.II.1). The passive optical networks (PONs) design was proposed as an approach to share the enormous fiber data transfer capacity among numerous clients through an aloof splitter, and subsequently improve the per client cost of Optical LAN [7,2]. PONs standardization work began in the 1990s when carriers anticipated fast growth in bandwidth demands [8,2]. The main goal of the passive optical networks (LANs) was to create the economy of scale and lower the cost of fiber-optic access systems by promoting common standards [9,2]. Major standards for emerged PONs, asynchronous transfer mode, broadband and gigabits PONs (respectively APONs, BPONs and GPONs) are today standardized and available in telecom markets [10,2]. The bidirectional point-to-multipoint network architecture, involved in Gigabit PON GPON-based systems, can deploy optical access lines from operator's central office to client sites [11,2].

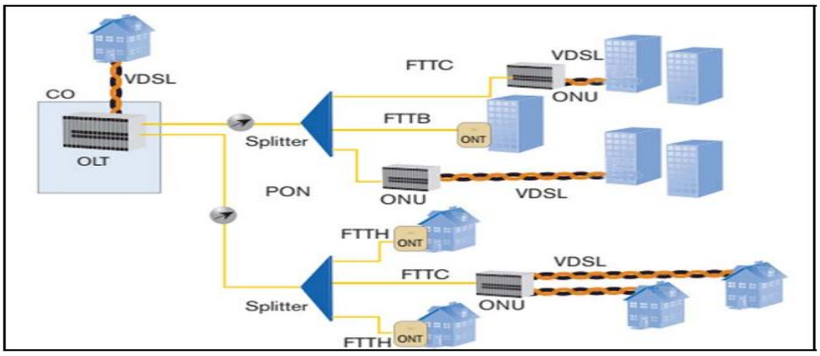


Figure II. 1 Typical Optical LAN networks [12,2]

II .2 Optical LAN System Description

Fig.II.2 focuses on typical OLANs architecture. At head-ends public switched telephone networks (PSTNs) and internet services are interfaced, via optical line terminals (OLTs), with optical distribution networks (ODNs), where (down/up)-stream 1490/1310 nm wavelengths are used respectively to transmit data and voice [12,2]. At 1550 nm, analog RF video services are converted to an optical format by optical video transmitters [13,2]. The 1550 and 1490 nm wavelengths are combined together by WDM couplers and transmitted downstream [14,2]. Nowadays, no standards for upstream video transmission are published, but IPTV is transmitted at present over 1490 nm [15,2]. Such couplers are used to multiplex downstream voice/data signals at 1490 nm with upstream voice/data signal at 1310 nm and downstream RF video signal at 1550 nm [9,2]. OLANs provide typical services (voice, data and video) to up to 32 subscribers [16,2].

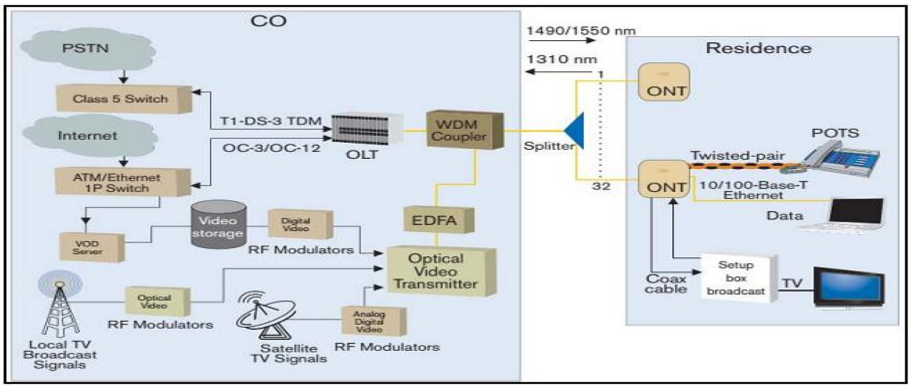
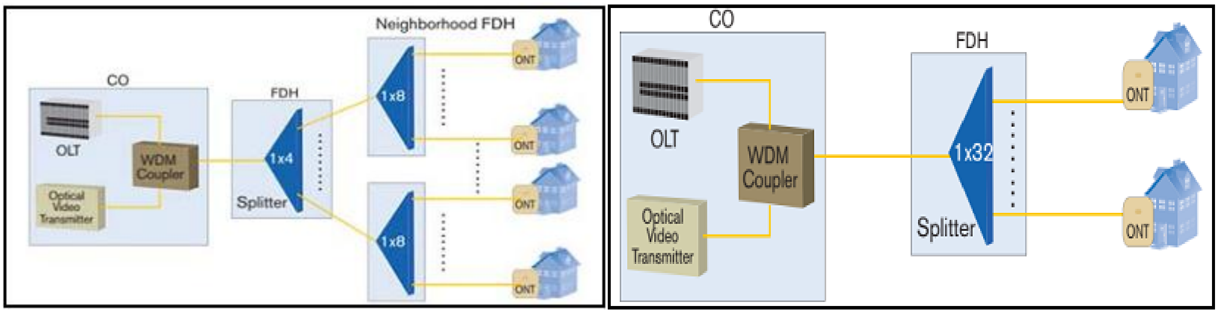


Figure II.2 Services in general architecture of optical LAN system [12,2]

Various designs for associating supporters of optical LAN frameworks exist. Although numerous splitters can likewise be utilized (Fig II.3 (a)), the simplest of them uses a solitary one (Fig II. 3(b)).



(a) (b)

Figure II. 3. Optical LAN network (a) with Single splitter (b) with multiple splitters [2]

Furthermore, other topologies such as the ring, star and bus technologies exist, and protections with different strategies are anticipated (FigII.4). In case of upstream direction (toward OLT) of a Point to Multipoint P2MP-OLAN, data collisions must be prevented from different ONT signals arriving at the same time at splitters, and time-division multiple access (TDMA) is used [16,2]. From each ONU back to OLT, TDMA can send burst or delayed data at a timeslot, and ONU transmission timeslots are granted by the OLT so as packets from various ONUs should not collide with each other [12,2].

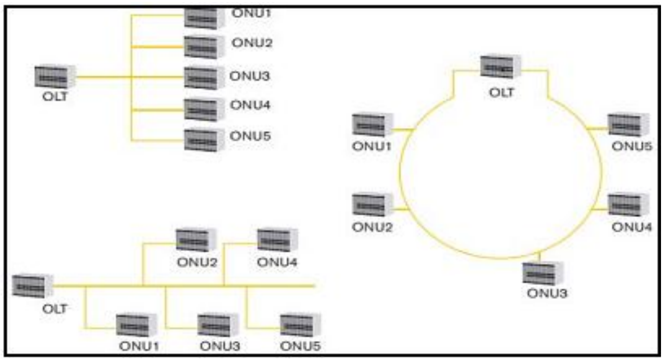


Figure II. 4 Optical LAN network topologies [2]

II.3 Multiplexing

Multiplexing is the process of combining multiple signals for transmission on a single transmission channel at the same time. in the telecommunications network the majority of transmission systems have more capacity than a single user requires. It is feasible to utilize the available bandwidth of optical fiber, coaxial cable, or a radio system into a single high-capacity system that is shared by several users [17].

II.3.1 Frequency and Time Division Multiplexing (FDM) and (TDM)

Using FDM each message is modulated to a distinct carrier frequency. The modulated messages are sent over the same channel, and at the destination, a bank of filters separates the messages Fig II.5. The system's frequency band is split into multiple narrowband channels; one for each user.Each narrowband channel is always reserved for one user. In the telephone network, FDM has been utilized in analog carrier systems. In analog cellular networks, for the duration of the call each user uses one FDM channel, using the same approach. Because the frequency-division approach is now utilized to allow several users to access the network at the same time, we name the process frequency-division multiple access (FDMA)[17].The Time-Division Multiplexing (TDM) is a more modern type of multiplexing that places various messages on the same channel.in time periods that do not overlap as illustrated in Fig II.5, each user channel uses a wider frequency band but only a small fraction of the time, one time slot in each frame. In addition to the user channels, at the receiver the switching circuit that separates the user channels (time slots) in the demultiplexe requires framing information. When the frame synchronization word is detected by the demultiplexer.it knows that this is the start of a new frame and the next time slot contains the information of user channel 1[17].

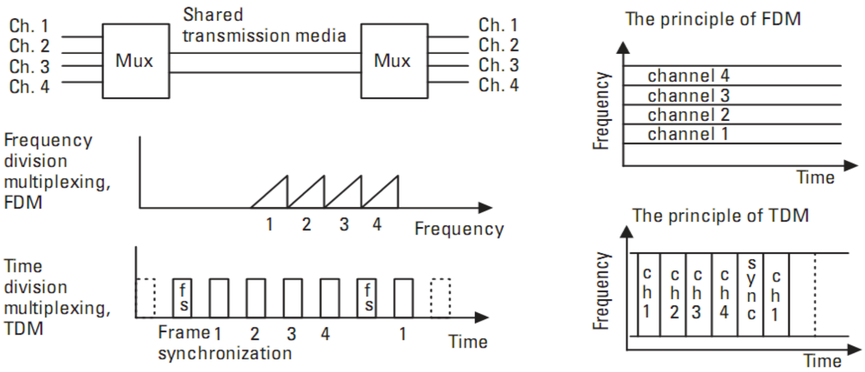


Figure II. 5 Multiplexing methods FDM and TDM [17]

TDM is utilized in high-capacity transmission systems such as optical line systems, as well as digital cellular networks, where it is referred to as time-division multiple accesses (TDMA). The time-division principle allows several users to access the network at the same time while using the same carrier frequency [17].

II.3.2 Plesiochronous Transmission Hierarchy

In the early 1970s, it was discovered that a main rate of 1.5 or 2Mbps is typically too slow for trunk or even local network transmission, this was discovered, and the ITU-T, then known as CCITT, standardized greater data rate transmission methods in the latter half of the 1970s, back then, digital systems mostly conveyed analog data, and end-to-end synchronization was rarely necessary. Plesiochronous digital hierarchy is the first defined digital higher-order transmission hierarchy (PDH) [17]. First, we'll go through the European higher-order multiplexing hierarchy.

II.3.2.1 European PDH (Plesiochronous Digital Hierarchy) for Higher-Order Multiplexing

PDH's higher-order multiplexers are free to run on their own clock frequencies. These standards are based on plesiochronous operation (or "almost the same data rate"), this enables for a small frequency variation between tributary signals multiplexed into a higher aggregate rate. As shown in Fig II.6, each multiplexer stage accepts four signals with lower data rates and combines them into a signal with a data rate that is a little bit over four times as high is the main idea of the European standard for higher-order multiplexers [17].The tributary frequencies may differ slightly, so they must be justified to the higher-order frame. This process, known as justification or stuffing, involves adding a number of justification bits to each tributary in order to ensure that the average tributary data rates are identical,these justification bits are extracted in the demultiplexer, and the original data rate for each tributary is generated[17].

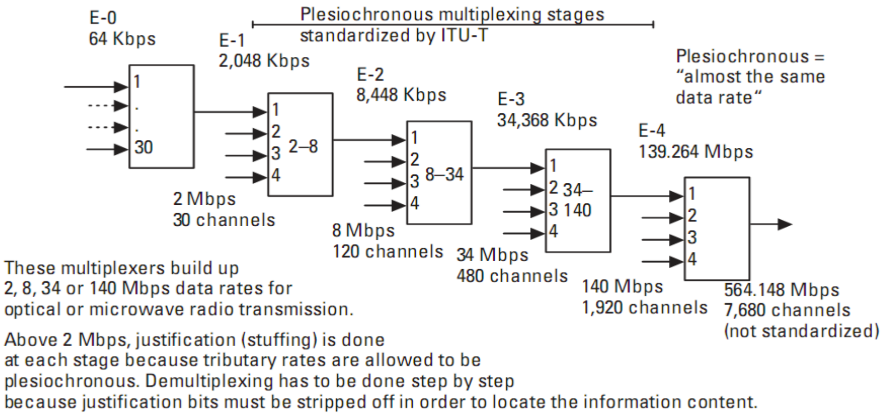


Figure II. 6 The PDH (European standard)[17]

At each hierarchy level, the tributary signals are bit interleaved to the aggregate data stream, meaning that the aggregate data stream comprises one bit from tributary 1, one bit from tributaries 2, 3, and 4, and so on[17]. Because additional bits in the frame are required for frame synchronization (frame alignment) and justification, the next level has a slightly higher rate than four times the nominal tributary rate. Justification bits are added to tributaries to equalize their data rates for framing, the frame also includes some spare bits that can be utilised. As shown Fig III.6, the multiplexers are linked for transmission through standard interfaces at 2, 8, 34, or 140 Mbps to isolate line terminal equipment or to a higher or dermultiplexer. Because the line interfaces of the line terminals for optical fiber, copper cable, and radio transmission are manufacturer specific, the vendor must be the same on both ends[17].

II.3.2.2 North American PDH for Higher-Order Multiplexing

DS1C (3.152 Mbps), DS2 (6.132 Mbps), DS3 (44.736 Mbps), and DS4 (274.176 Mbps) are higher-order rates of the North American PDH as shown FigII.7 [18]. The DS levels that are being merged are identified by the names of the higher-level multiplexers. M13 in Fig II.7, for example, contains inputs from level DS1 and from outputs level DS3.Fig II.7 shows the higher-order bit rate for each multiplexer a little bit higher than the total of the tributary data rates. In addition to tributary signals, the aggregate data stream at each level comprises framing information and thestuffing bits that are used to explain tributary data rates, which may have slightly different, in to the higher-order frame. These stuffing bits are taken off in the demultiplexer, and the original tributary rate is produced [17].

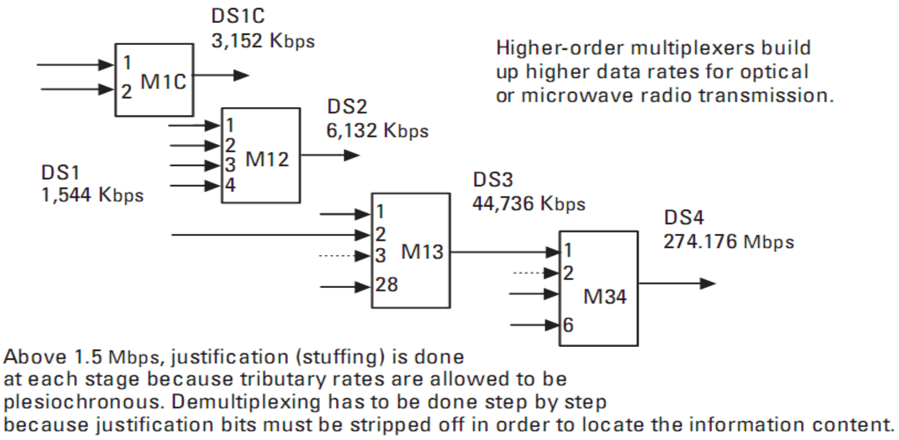


Figure II. 7 North American PDH [17]

II.3.3 SDH and SONET

More than 20 years ago, the PDH higher-order systems were standardized. By the end of the 1980s, a significant amount of optical fiber cable had been deployed, and analog networks had been converted to digital networks. The researchers then concluded that new standards were needed to fulfill future demands [17].The following are some of the issues with the PDH standards:

- Due to stuffing (justification), access to a tributary rate necessitates step-by-step demultiplexing. Optical interfaces are not standardized but vendor specific.
- To utilize optical cables, a separate multiplexer for each level is required (for example, multiplexing from 2 to 140 Mbps in European PDH requires 21 pieces of multiplexing equipment) as well as separate line terminals.
- European and American standards are not compatible.
- Network management features and interfaces are vendor dependent.
- High data rates (above 140 or 274 Mbps) are not standardized.

In the middle of the 1970s, a new transmission technique was developed to make better use of optical networks and modern digital technologies. In the United States, this system is known as the synchronous optical network (SONET). By the end of the 1980s, ITU-T had developed its own global standard, known as SDH. SDH (Synchronous digital hierarchy) is an international extension of SONET that was built on SONET but modified for use in European networks. As demonstrated in Table II.1, the operational principles of SONET and European SDH are quite similar, and they employ the same data rate at some levels [17].

Table II.1 Data Rates of SONET (United States) and Corresponding SDH Data Streams (Europe)[17]

OC-N Optical Carrier Level	STS-N Electrical Level	Data Rate (Mbps)	SDH STM-N
OC-1	STS-1	51.84	
OC-3	STS-3	155.52	STM-1
OC-12	STS-12	622.08	STM-4
OC-24	STS-24	1244.16	STM-8
OC-48	STS-48	2488.32	STM-16
OC-192	STS-192	9953.28	STM-64

Figure II.8 shows European SDH data rates as well as an example of SDH equipment. SDH is a standardized multiplexing system for synchronous tributaries and plesiochronous such as 1.5, 2, or 34 Mbps.

The main advantages of SDH over PDH standards are as follows:

- The optical transmission data rates are standardized (i.e., vendor independent).
- Standards include a variety of systems, such as terminal, add/drop, and cross-connection systems. They also make SDH networks more adaptable than PDH systems, which only offer terminal multiplexer functionality.
- It is simple to obtain access to tributary data rates (no step-by-step multiplexing is required).
- The system is tolerant against synchronization and other system faults. Operators can move from a problematic line to an operating line using standardized redundancy mechanisms.

In the transport system, SDH is replacing PDH systems, it means the flexible high-capacity transmission network that is utilized to carry all sorts of information through transport network. The term "flexible" refers to the ability of telecommunications operators to quickly alter the structure of the transport network from the centralized management system. This reduces the delivery times for leased lines [17-19].

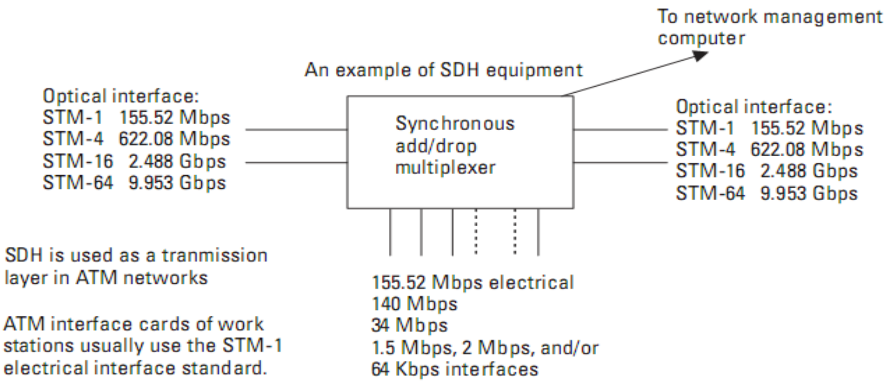


Figure II.8 The synchronous digital hierarchy of ETSI [17]

II.3.3.1 Multiplexing Scheme in SDH

The transmission data streams of SDH are called synchronous transport modules (STMs) as shown in Table II.1, and they are precise multiples of STM-1 at the 155.52 Mbps data rate, to achieve a higher transmission data rate, STM-1 data are simply byte interleaved with other STM-1 data streams,there is no additional frame information added, byte interleaving implies that an STM-4 signal, for example, comprises a byte (8bits) from the first STM-1 tributary, then from the second, third, and fourth tributaries, and finally from the first one again. All STM-1 frames are received individually by the demultiplexer [17-20], the STM-1 frame is repeated 8,000 times per second, which is the same rate as the PCM sampling rate, each 8-bit speech sample is now displayed in a 155.52 Mbps data stream. We can demultiplex one speech channel by picking up 1byte from each STM-1 frame when PCM coding is synchronized to the same source as SDH systems. [17,19].

II.3.3.2 Data Rates of North American SONET

The synchronous transport signal level 1 (STS-1) is the fundamental SONET module, equivalent to SDH's STM-1,these modules have a bit rate of 51.840Mbps and are synchronously multiplexed into higher-order signals STS-N. For optical transmission, each STS-N signal has a corresponding optical signal termed an optical carrier (OC-N). The table II.1 shows SONET data rates and related signal levels for European SDH.An STS-1 signal is made up of frames, and the frame duration is 125 µs (8,000 times a second , that is, equal to the PCM sampling rate), the same as in SDH Each frame has 810 bytes, for a total bit rate of 51.840 Mbps. In each frame, 27 bytes are utilized for transport overhead information such as frame synchronization and pointers, with the rest bytes being used for payload [17-20]. SONET and SDH were initially intended to transmit 64Kbps PCM channels[17-20].

II .4 Channel Multiplexing Techniques

II .4.1 Time-Division Multiplexing (TDM)

TDM is frequently used in the electrical domain to create digital hierarchies for communications systems, electrical TDM becomes difficult to implement at data rates exceeding 40 Gb/s because of the restrictions imposed by high-speed circuits, the optical TDM provides a solution (OTDM), during the 1990s ,the OTDM technique was studied extensively [21,22] .

II. 4.1.1 Channel Multiplexing

At bit rate B, several optical signals share the same carrier frequency in OTDM lightwave systems and are optically multiplexed to produce a composite bit stream at bit rate NB, where the number of channels is N. For this aim, a variety of multiplexing methods can be utilized [22], based on the delay-line method,it requires the use of a laser capable of producing a periodic pulse train at a repetition rate equal to the single-channel bit rate B,furthermore, the laser should generate pulses of width T_p such that $T_p \prec T_B = (NB)^{-1}$ to guarantee that each pulse fits inside the time slot allocated to it T_B After any necessary amplification, the laser output is divided evenly into N branches.In each branch,a modulator blocks the 0 bit pulses and generates N separate bit streams at the bit rate B[23].
A delay method that can be easily implemented optically is used to multiplex N bit streams, the bit stream in the *n*th branch is delayed by *(n - l)/(NB)* in this method, where *n*= l,...,N. The outputs of all branches are then added together to produce a composite signal. It should be clear that the multiplexed bit stream generated by such a method has a bit slot corresponding to the bit rate NB [23].Furthermore, N successive bits belong to N distinct channels in each interval of duration B^{-1}.

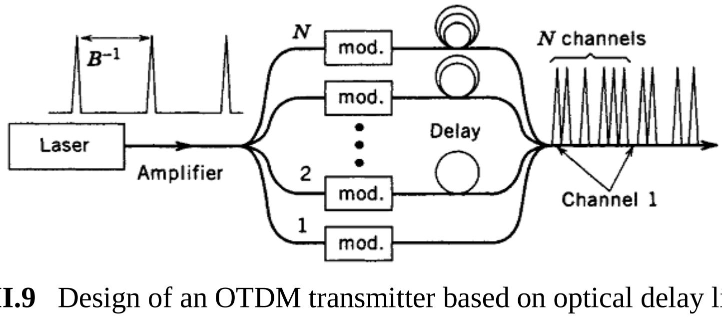


Figure II.9 Design of an OTDM transmitter based on optical delay lines[23]

II.4.1.2 Channel Demultiplexing

Individual channel demultiplexing from an OTDM signal requires the use of electro-optic or all-optical methods, several systems have been devised, each with its own set of advantages and disadvantages [24,25]. Fig II.10 shows three of the designs covered in this section,a clock signal a periodic pulse train at the single-channel bit rate is required for all demultiplexing methods. For electro-optic demultiplexing, the clock signal is in electric form, while for all-optical demultiplexing, it is an optical pulse train [23].

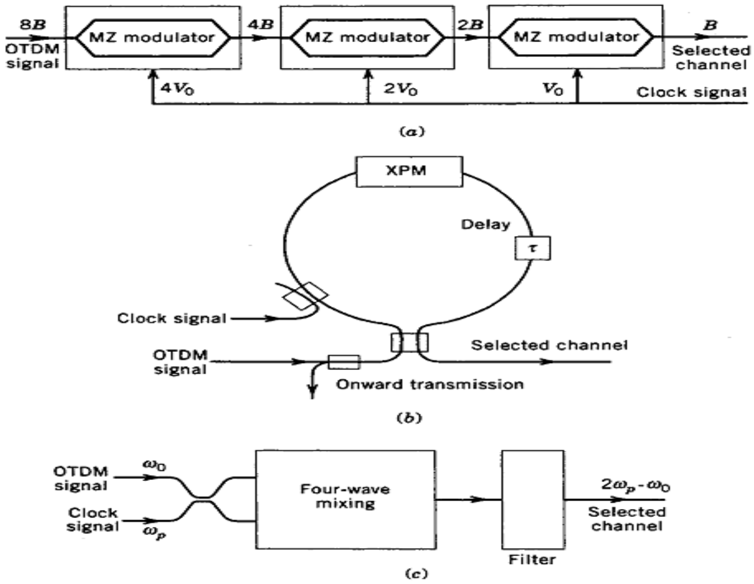


Figure II.10: Demultiplexing schemes for OTDM signals based on (a) cascaded LiNbC>3 modu-Lators , (b) XPM in a nonlinear optical-loop mirror, and (c) FWM in a nonlinear medium[23].

The electro-optic method employs a series of MZ-type LiNb03 modulators, by rejecting alternating bits in the incoming signal; each modulator reduces the bit rate by half. As a result, an 8-channel OTDM system necessitates three modulators, each controlled by the same electrical clock signal (see Fig II .10), but with differing voltages equal to $4V_0$, $2V_0$, and V_0, respectively, where the voltage necessary for one arm of the MZ interferometer is V_b to change by one phase[23].
As illustrated in Fig II.10 (b), some all-optical methods include a nonlinear optical loop mirror (NOLM) formed from a fiber loop whose ends are linked to the two output ports of a 3-dB fiber coupler, because NOLM completely reflects its input when the counter propagating waves experience the same phase shift throughout a single round trip,so the NOLM is referred to as a mirror [23]. An NOLM's demultiplexing process is dependent on the XPM [26-27]. in Fig employs FWM in a nonlinear medium is the third technique for demultiplexing, the OTDM signal, together with the clock signal, is launched into a nonlinear medium, the clock signal serves as the pump for the FWM process,only in time slots where a clock pulse overlaps with the signal pulses of the channel that needs to be demultiplexed may indeed FWM produce a pulse at the idler wavelength[23]. resultig the pulse train at the new wavelength is an identical replica of the demultiplexed channel. an optical filter is utilized to isolate the demultiplexed channel from the OTDM and clock signals, because of its ultrafast nonlinearity and capacity to maintain the state of polarization despite environmental perturbations, polarization-preserving fiber is frequently employed as the nonlinear medium for FWM[23].

II .4.2 Wavelength Division Multiplexed (WDM)

Large transmission capacities have been achieved using optical fiber communication systems. However, traditional TDM (Time Division Multiplexing)-based bit rate increases are unable to meet the increasing demand for increased transmission capacity generated by data communication and the

Internet. Due to the urgent need for more transmission capacity, the system planner decided to employ WDM systems rather than TDM systems to maximize the usage of existing optical fibers [28].In 1995, the first commercial WDM system was deployed on a significant scale. WDM was at the forefront of the rapid expansion of optical communications. Three research laboratories announced in early 1996 that prototype transmission systems have broken past the Terabit/second barrier for the amount of data transported by a single fiber. A WDM research transmission experiment revealed a capacity of 10 Tb/s per fiber five years later, in 2001, perfectly on time for the factor-100-per-decade growth rate [28] .

WDM systems are believed to be the most cost-effective approach to deal with growing transmission capacity while still utilising existing transmission technology. The overall throughput transmission capacity of WDM systems can be enhanced by the number of lasers by utilizing multi-channel single-frequency lasers such as distributed feedback lasers with slightly varying wavelengths defined by International Telecommunication Union ITU (channels) [28].WDM is based on the concept of combining multiple optical signals into a single optical cable while sending each signal at a different wavelength. The information for each of the utilized frequencies is modulated by the transmitter. In the multiplex, all of the contributions from the *n*-channels are combined into one optical fiber. Fig II.11 depicts a simple principl. [29,23]. The total bit rate-distance product, BL, is obtained when N channels at bit rates B_1, B_2,… and B_N are transmitted simultaneously across a fiber of length L.

$$BL = (B_1 + B_2 + ... + B_N)L \qquad (II.1)$$

By broadcasting 10 channels at 2 Gb/s across 68.3 km of standard fiber with a channel spacing of 1.35 nm, an early experiment in 1985 proved the BL product of 1.37 (Tb/s)-km[30]. It is common to define a measure for a WDM system's spectral efficiency as [30]

$$\eta_s = B/\Delta\nu_{ch} \qquad (II.2)$$

Where *B* denotes the channel bit rate and the channel spacing in frequency units is $\Delta v_{ch.}$

It should be noted that the terms WDM wavelength and WDM channel are not equivalent. WDM wavelength refers to the center wavelength of an optical signal. The term "WDM channel" refers to an optical signal communications line defined by a central wavelength and a spectral passband. It is possible to have complete duplex, half duplex, or simplex [23].

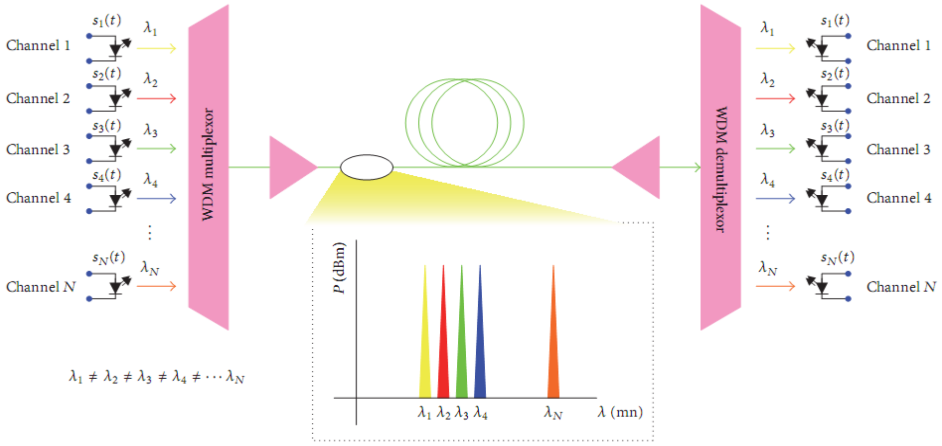


Figure II .11 Simplified principle of WDM [29]

WDM techniques are split into three categories:

Wide wavelength division multiplex(WWDM), dense wavelength division multiplex(DWDM), and coarse wavelength division multiplex(CWDM).

- **WWDM** is one of the oldest kinds, yet it is still widely used due to its cost-effectiveness. The separation of information-bearing wavelengths is more than or equal to 20nm in four of the most often used wavelengths [29].
- In **DWDM**, the spacing between information-carrying wave lengths is just 0.8nm, and with higher frequency, a separation of 0.4nm is possible. UDWDM (ultra dense wavelength division multiplex) systems are currently available. The gap in these systems is as small as 0.2nm or even 0.1nm [29].it is possible to transmit tens or hundreds of parallel optical lines using DWDM systems. Recommendation individual transmission channels in the wavelength range of 1490nm (200.95THz) to 1620nm (186THz) are defined by ITU-TG.694.1 and are included in the S, C, or L band [31,32].
- **CWDM** originated as a less expensive variant of DWDM. The requirements for CWDM components are less stringent and technologically demanding than those for DWDM components. The spacing between separate channels is specified as 20nm in the ITU-TG.694.2 recommendation [33,34].

II .4.2.1 Semiconductor Materials

The relationship between materials and wavelength is seen in Fig II .12. Lasers with a wavelength of 1480 nm can be made, the established technology for telecommunication lasers emitting at 1300 nm and 1550 nm may be used; a standard GaInAsP quantum well (both lattice-matched and strained-layer) on InP can emit 1480 nm light. On a GaAs substrate, an InGaAs strained-layer quantum well may emit light at 980 nm. [28].On an InP substrate, a GaxInl-,AsyP1-y quaternary compound was used to produce 1480nm lasers. 980nm lasers, on the other hand, cannot be made using lattice-matched material[28].The wavelength of approximately 980 nm emitted by semiconductor lasers has been the forbidden wavelength region, which cannot be covered by short wavelength GaAs-based lasers (wavelength less than 900 nm) and long wavelength InP-based lasers (wavelength longer than 1200nm) [28].The concept of strained-layer quantum wells, on the other hand, enabled the development of 980nm lasers and the rapid advancement of the epitaxial growth technique for growing high-quality very thin strained-layer material. Intentionally lattice-mismatched In,GaAs layer on GaAs substrate can be used to fabricate 980 nm lasers. In,GaAs strained-layer has a large lattice constant with respect to GaAs[28].

If the layer thickness is controlled within a critical thickness calculated by Mathew’s law, the layer can be grown with high crystalline quality on GaAs substrate even if the InGaAs layer has a large amount of strain. This condition is approximately given by $\varepsilon * L_z < 20\text{nm}\%$, where ε is the amount of strain and L_z, is the layer thickness[28].For 1480nm lasers, strained-layer GaInAsP is utilized instead of a lattice-matched system on an InP substrate because the idea of strained-layer quantum may substantially enhance the lasing properties. Let's go through quantum wells and strained-layer quantum wells, which are employed in high-power 980 nm and 1480 nm lasers. To demonstrate quantum effects, quantum wells are constructed up of two distinct materials with a layer thickness of less than 20 nm. Because carriers are efficiently confined to the quantized state, high material gain may be attained with fewer carriers.

The quantum well has formed. The introduction of compressive strain into quantum wells, in particular, can change the valence band structure in such a way that the effective mass of heavy-hall becomes light. As a result, reduced carrier density can satisfy the Bernard-Durgaffourg requirement (Fermi-level separation greater than energy bandgap)[28].

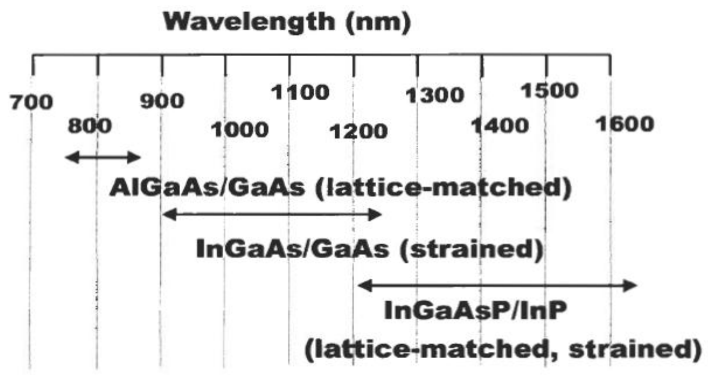


Figure II .12 Active layer materials to get a wavelength from 700nm to 1600nm [28]

II. 4.2.2 WDM Components

In fiber-optic communication networks the use of WDM technology requires the development of several new optical components. The Multiplexers which aggregate the output of many transmitters and launch it into an optical fiber ; the demultiplexers which isolate the received multichannel signal into individual channels destined to different receivers; the tunable optical filters which filter out one channel at a specific wavelength that can be changed by tuning the passband of the optical filter; the optical transmitters where many avelengths that can be adjusted over a few nanometers; Add-drop multiplexers and optical routers are devices that can spread a WDM signal to several ports.

II.4.2.2.1 Tunable Optical Filters

Optical filters are frequently the building blocks of more complicated WDM components, a tunable optical filter's function in a WDM system is to choose a desired channel at the receiver. Fig II.13 shows the selection mechanism schematically. The filter bandwidth must be large enough to transmit the intended channel but, at the same time, small enough to block the neighboring channels [23].The desirable properties of a tunable optical filter include:

- A broad tuning range to increase the number of channels available for selection.
- Quick adjusting speed to reduce access time. Low cost.
- Negligible crosstalk to avoid interference from adjacent channels.
- Insertion loss is minimal.polarization insensitivity
- Stability in the face of environmental variations (humidity, temperature, vibrations, etc).

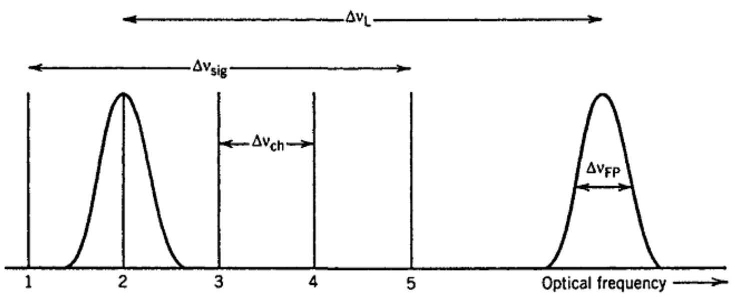


Figure II .13 Channel selection through a tunable optical filter[23]

a/ Fabry-Perot Filters

A Fabry-Perot (FP) interferometer, which is a cavity created by two mirrors, can function as a tunable optical filter if its length is electrically controlled by a piezoelectric transducer [see Fig II.14 (a)]. A FP filter's transmittivity peaks at wavelengths corresponding to longitudinal-mode frequencies, resulting the frequency spacing between two successive transmission peaks, referred to as the free spectral range, is given by [23]

$$\Delta\nu_L = c/(2n_g L) \qquad \text{(II.3)}$$

Where n_g denotes the group index of the intracavity material for a FP filter of length L. If the filter is designed to pass a single channel (as shown in Fig II.13), the multichannel signal's combined bandwidth $\Delta\nu_{sig} = N\Delta\nu_{ch} = NB/\eta_s$ must be less than $\Delta\nu_L$, where N denotes the number of channels, η_s denotes spectral efficiency, and B is the bit rate, the filter bandwidth $\Delta\nu_{FP}$ (the width of the transmission peak in Fig II.13) should be large enough to pass the entire frequency contents of the chosen channel. In most cases, $\Delta\nu_{FP} \sim B$, resulting the number of channels is limited by (N the number of channels that a FP filter can resolve)[23,35]

$$N \prec \eta_s(\Delta\nu_L/\Delta\nu_{FP}) = \eta_s F \qquad \text{(II.4)}$$

Where $F = \Delta\nu_L/\Delta\nu_{FP}$ is the finesse of the FP filter.

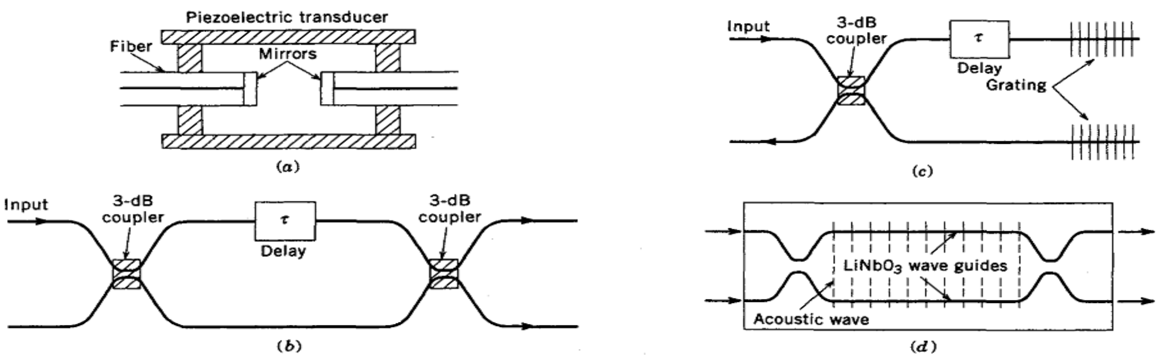


Figure II.14 Four kinds of filters based on various interferometric and diffractive devices: (a) Fabry-Perot filter; (b) Mach-Zehnder filter; (c) grating-based Michelson filter; (d) acousto-optic filter. The shaded area represents a surface acoustic wave[23]

b/ Mach-Zehnder Filters

To create a tunable optical filter a series of Mach-Zehnder (MZ) interferometers can be utilized [36,37]. A MZ interferometer is easily built by connecting the two output ports of one 3-dB coupler to the two input ports of another 3-dB coupler [see Fig II.14(b)]. The input signal is divided equally into two parts with the first coupler, which acquire distinct phase shifts (if the arm lengths are made different) before interfering at the second coupler, because the relative phase shift varies with wavelength, the transmittivity T(v) is also wavelength dependent where $T(\nu) = |H(\nu)^2| = \cos^2(\pi\nu\tau)$, where $\nu = \omega/2\pi$ denotes the frequency and τ denotes the relative delay in the two arms of the MZ interferometer [38].

c/ Grating-Based Filters

The wavelength selectivity offered by a Bragg grating is used in a different family of tunable optical filters. A simple example of grating-based optical filters are Fiber Bragg gratings[39]. A fiber grating functions as a reflection filter in its most basic form, the center wavelength of which may be controlled by varying the grating period, and its bandwidth may be adjusted by varying the grating strength or slightly chirping the grating period. In reality, the reflective nature of fiber gratings is frequently a limitation, requiring the employment of an optical circulator [23]. A phase shift in the grating's center can transform a fiber grating into a narrowband transmission filter [40]. Many different approaches may be utilized to create fiber grating-based transmission filters. In one technique, fiber gratings are utilized as FP filter mirrors, resulting in transmission filters with free spectral ranges ranging from 0.1 to 10 nm [41]. Transmission filters can also be realized using other types of interferometers, such as the Sagnac and Michelson interferometers. Fig II.14(c) shows a Michelson interferometer constructed using a 3-dB fiber coupler and two fiber gratings functioning as mirrors for the Michelson interferometer's two arms [42]. The majority of these systems may also be realized as a planar lightwave circuit by constructing silica waveguides on a silicon substrate [23]. Many other grating-based filters for WDM systems have been created[43,44].The InGaAsP/InP material combination is utilized to create planar waveguides operating near 1.55µm in one method adapted from DFB-laser(Distributed Feedback) technology.The wavelength selectivity is given by a built-in grating,the Bragg wavelength of which is adjusted electrically through electrorefraction [43].

d/ Acousto-Optic Filters

In another class of tunable filters, Acoustic waves are used to dynamically create the grating. These filters, known as acousto-optic filters, have a broad tuning range (> 100 nm) and are well suited for WDM applications [45,46]. The photoelastic effect, which happnes when an acoustic wave propagates through an acousto-optic material creates periodic changes in the refractive index, is the basic process behind the operation of acousto-optic filters (corresponding to the regions of local compression and rarefaction)[23]. The acoustic wave, in effect, generates a periodic index grating that may diffract an optical beam. This acoustically generated grating produces wavelength selectivity. When a transverse electric (TE) wave with the propagation vector k is diffracted from this grating, the polarization of the wave can be changed from TE to transverse magnetic (TM) if the phase-matching condition $K^{'} = K \pm K_a$ is satisfied. Where k' and K_a are the wave vectors associated with the TM and acoustic waves, respectively [23]. The LiNb03 waveguide technology is frequently utilized for WDM applications because it can produce compact, polarization independent acousto-optic filters with a bandwidth of around 1 nm and a tuning range of more than 100 nm [47]. The basic architecture, seen schematically in Fig II.14 (d), has two polarization beam splitters, two LiNbO3 waveguides, and a surface-acoustic-wave transducer, all of which are integrated on the same substrate. The first beam splitter divides the incident WDM signal into orthogonally polarized components. Because of an acoustically induced change in its polarization direction, the channel whose wavelength λ fulfills the Bragg requirement $\lambda = (\Delta_n)\Lambda_a$ is directed to a different output port by the second beam splitter; all other channels travel to the other output port.

e/ Amplifier-Based Filters

Another type of tunable optical filter works on the idea of amplification of a selected channel. As an optical filter, any amplifier with a gain bandwidth less than the channel spacing can be utilized. Tuning is done by changing the wavelength at which the gain peak appears. SBS (stimulated Brillouin scattering), which occurs naturally in silica fibers [27], can be used to selectively amplify one channel, however the gain bandwidth is relatively limited (100 MHz). The SBS phenomenon is regulated by a phase-matching condition similar to that seen in acousto-optic filters and includes interaction between optical and acoustic waves. SBS occurs only in the backward direction and results in a frequency shift of about 10 GHz in the 1.55-um region [23]. To utilize SBS amplification as a tunable optical filter, a CW pump beam is launched at the receiver end of the optical fiber in the opposite direction as the multichannel signal, and the pump wavelength is adjusted to choose the channel. The pump beam transmits some of its energy to a channel that is exactly the Brillouin shift lower than the pump frequency.

II.4.2.2.2 Multiplexers and Demultiplexers

In every WDM system multiplexers and demultiplexers are critical components. Demultiplexers are classified into two categories based on their need for a wavelength-selective mechanism. Diffraction-based demultiplexers spatially scatter incident light into distinct wavelength components using an angularly dispersive device, such as a diffraction grating. In interference-based demultiplexers, devices such as optical filters and directional couplers are employed. Because optical waves in dielectric media have intrinsic reciprocity, the same device can be used as a multiplexer or a demultiplexer in both circumstances, depending on the direction of propagation. [23,48].

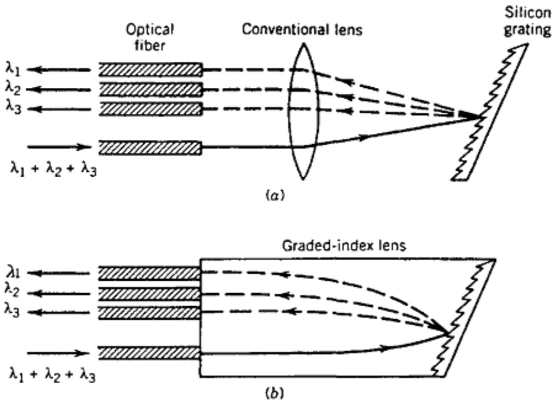


Figure II.15 Grating-based demultiplexer making use of (a) a conventional lens and (b) a graded-index lens[23]

The phenomenon of Bragg diffraction from an optical grating is used in grating-based demultiplexers [49,50]. The layout of two such demultiplexers is shown in Fig II.5. The input WDM signal is focused onto a reflection grating, which spatially separates distinct wavelength components, and then focused onto individual fibers by a lens. The use of a graded-index lens facilitates alignment and results in a relatively small device. A concave grating can be used to remove the focusing lens altogether. The concave grating may be incorporated into a silicon slab waveguide for a more compact design [51] , numerous elliptical Bragg gratings are etched using silicon technology in a different technique [49]. If the input and output fibers are placed at the elliptical grating's two foci, and the grating period Λ is adjusted to a specific wavelength λ_0 using the Bragg condition $2\Lambda n_{eff} = \lambda_0$, where n_{eff} (is the effective index of the waveguide mode), the grating will selectively reflect and focus that wavelength onto the output fiber[23]. The MZ filter-based demultiplexers have received the greatest attention. Just like a tunable optical filter several MZ interferometers are coupled to produce a WDM demultiplexer. [52,53].

Using fiber Bragg gratings, all-fiber demultiplexers may also be made. In one method, an $1\times N$ fiber coupler is turned into a demultiplexer by constructing a phase-shifted grating at each output port, therefore opening a narrowband transmission window (0.1 nm) within the stop band [40].

By combining several directional couplers, multiplexers can be constructed. When the channel spacing is relatively large (> 10 nm) multiplexers based on fiber couplers can only be utilized, making them primarily appropriate for coarse WDM applications [23].

In terms of system architecture, integrated demultiplexers with minimal insertion losses are desirable. An interesting method employs a phased array of optical waveguides that functions as a grating. These gratings are known as arrayed waveguide gratings (AWGs), and they have received a lot of interest since they may be made out of silicon InP, or LiNbO3 technology [54,55] . AWGs can be used for a variety of WDM applications; Demultiplexers of this type were developed in the 1990s and were commercially available by 1999. They can resolve up to 256 channels with as little as 0.2 nm spacing. A combination of multiple appropriately designed AWGs can raise the number of channels to over 1000 while retaining a 10-GHz resolution [56].

II.4.2.2.3 Add-Drop Multiplexers and Filters

Add-drop multiplexers are necessary in wide-area and metro-area networks when one or more channels must be dropped or added while maintaining the integrity of existing channels [57]. The architecture of a reconfigurable optical add-drop multiplexer (ROADM) with a bank of optical switches between a demultiplexer-multiplexer pair is shown in Fig II.16(a). The demultiplexer separates all channels, optical switches drop, add, or pass certain channels, and the multiplexer recombines the entire signal. The novel component of such multiplexers is the optical switch, which may be manufactured using a variety of technologies such as LiNbO3 and InGaAsP waveguides [23]. If only a single channel has to be demultiplexed and there is no need for active control of separate channels,A considerably simpler multiport device can be used to send a single channel to one port while transferring all other channels to another. Add-drop filters are devices that reduce the need to demultiplex all channels. Because they block a certain channel while not interfering with the WDM transmission. Several types of add-drop filters have been created since the advent of WDM technology [58,59]. The most fundamental design involves a sequence of interconnected directional couplers to construct a MZ chain, similar to the previously stated MZ filter.Bragg gratings' wavelength selectivity may also be utilized to create add-drop filters. A Bragg grating is constructed in the center of a directional coupler in one technique known as the grating-assisted directional coupler [60]. InGaAsP/InP or silica waveguides can be used to make such devices in a compact form. An all-fiber device, on the other hand, is frequently selected to avoid coupling losses. Two identical Bragg gratings are created on the two arms of a MZ interferometer utilizing two 3-dB fiber couplers in a common approach.

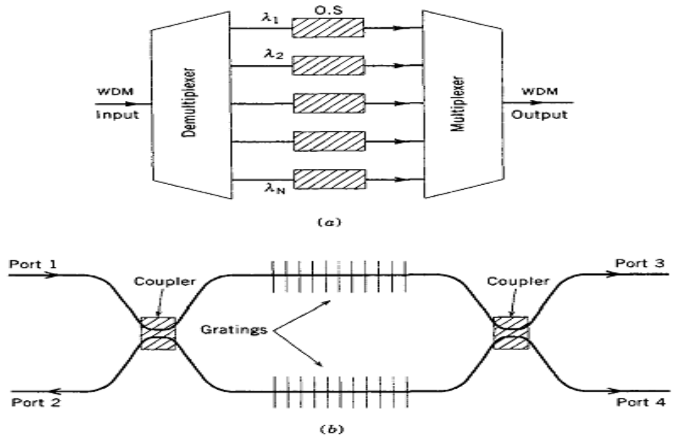


Figure II.16 (a) A generic add-drop multiplexer based on optical switches (OS); (b) an add-drop filter made with a Mach-Zehnder interferometer and two identical fiber gratings[23]

Fig II.16 (b) depicts the operation of such an add-drop filter [23]. Assume that the WDM signal is incident on the filter's port 1. The channel is completely reflected and appears at port 2 because its wavelength Xg falls inside the stop band of the two identical Bragg gratings. The remaining channels, which appear at port 4, are unaffected by the gratings . If a signal at that wavelength is injected from port 3, the same device can add a channel at that wavelength [61,62].

II.4.2.2.4 A Directional Couplers

In an optical network, a directional coupler is used to combine and split signals. As shown in Fig II.17, a 2 2 coupler has two input ports and two output ports. The most common couplers are fused fiber couplers, which are created by fusing two fibers together in the center. Also couplers can be created in integrated optics utilizing waveguides. In integrated optics, waveguides are used. Fig II.17 shows a 2 2 coupler that takes a fraction α of the power from input 1 and places it on output 1 and the remaining fraction $1-\alpha$ on output 2. Similarly, afraction $1-\alpha$ of the power from input 2 is distributed to output 1, and the remaining power is transferred to output 2. The coupling ratio is what we call it. These couplers, also known as taps, are constructed with values near to 1, generally 0.90–0.95 [63]. Over an usefully large range, the coupler can be configured to be either wavelength selective or wavelength independent (also known as wavelength flat). In a wavelength-independent device, α is independent of the wavelength; in a wavelength-selective device, α depends on the wavelength [63].

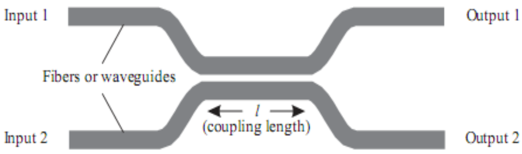


Figure II.17 A directional coupler [63]

II.4.2.2.5 WDM Transmitters and Receivers

Most WDM systems include a large number of DFB lasers, the frequencies of which are carefully selected to match the ITU frequency grid. When the number of channels grows big, this method becomes impractical. There are two options. Monolithically integrated WDM transmitters operating at 1.55 /im with channel spacing of 1 nm or less were developed and commercialized utilizing InP-based photonic integrated-circuit (PIC) technology only after 2001 [64,65]. WDM transmitters have been designed using a variety of techniques. Using passive waveguides, the output of multiple DFB or DBR semiconductor lasers, each individually adjustable through Bragg gratings, is coupled in one approach [66,67]. A built-in amplifier amplifies the power of the multiplexed signal, increasing the transmitted power. 16 gain-coupled DFB lasers were combined in a 1996 system, and their wavelengths were adjusted by changing the width of the ridge waveguides[68]. In a different technique, sampling gratings of varying periods are utilized to accurately adjust the wavelengths of an array of DBR lasers [69]. Because of the complexity of such systems, integrating more than 16 lasers on the same chip is difficult. A waveguide grating is incorporated into the laser cavity in a new way to enable lasing at several wavelengths at the same time. AWGs are frequently used to multiplex the output of several optical amplifiers or DBR lasers [70,71]. In a 1996 demonstration of the basic idea, an intracavity AWG was used to achieve simultaneous operation at 18 wavelengths (separated apart by 0.8 nm)[70]. 12 tunable DFB lasers were integrated on the same InP chip in a 2002 transmitter, and their outputs were merged using a micro-electro-mechanical system (MEMS) within a butterfly module [64]. A transmitter of this type may deliver up to 20 mW of fiber-coupled power at ITU wavelengths in the C band with spacing of 50 GHz accurately set by a wavelength locker. Fully integrated large-scale PIC transmitter chips were developed and marketed by 2005. A 10-channel receiver PIC chip was developed to match WDM transmitter[72].By 2006, this method has been expanded to the fabrication of 40-channel WDM transmitters with a data rate of 40 Gb/s per channel [73]. By 2009, 50-wavelength fiber lasers covering the whole C band at 100 GHz were available.The concept of channel spacing was created [74]. A unique approach to WDM sources use spectral slicing to produce WDM transmitters with more than 1000 channels [75,76]. A multipeak optical filter, such as an AWG, is used to spectrally slice the output of a coherent, wideband source. In a 2000 experiment, this approach generated 1000 channels with 12.5-GHz channel spacing [77]. Another experiment [76] achieved 150 channels with a channel spacing of 25 GHz in the C band, encompassing the wavelength range 1530-1560 nm. The SNR of each channel exceeded 28 dB, indicating that the source was suitable for dense WDM applications [26,78,79]. At the receiver end, multichannel WDM receivers have been created because their use can simplify system design and reduce overall costs.

II.4.3 Orthogonal Frequency-Division multiplexing (OFDM)

Orthogonal frequency-division multiplexing (OFDM) is a well-known multiplexing technique in the context of cell phones and other wireless applications,OFDM employs a large number of microwave subcarriers [28], the basic idea behind OFDM makes use of the discrete Fourier transform (DFT) operation [80,81]. Fig II.18 shows schematically the designs of typical OFDM transmitters and receivers. At both the transmitter and receiver ends, the electrical bit stream is subjected to considerable digital signal processing (DSP). The DFT and inverse DFT (IDFT) procedures are the most essential, Serial data is parallelized (S/P operation) and transformed into a symbol stream at the transmitter end. To perform the inverse DFT operation with the help of a fast Fourier transform method, the number N of parallel streams is selected in the form of $N = 2^n$, The number n is usually between the range of 6 to 10. After the IDFT process, each parallel stream represents a microwave subcarrier, A digital-to-analog converter (D/A operation) is used to produce a composite signal comprising all subcarriers after adding a cyclic prefix or guardband (GI operation). After utilizing a microwave oscillator to upshift signal frequencies by f_{LO} (LOl), the signal takes the form [23].

$$s(t) = \sum_{m=-\infty}^{\infty} \sum_{k=1}^{N} c_{km} s_k (t - mT_s), \quad s_k(t) = h(t) \exp[-2\pi i (f_{LO} + f_k) t] \qquad \text{(II.5)}$$

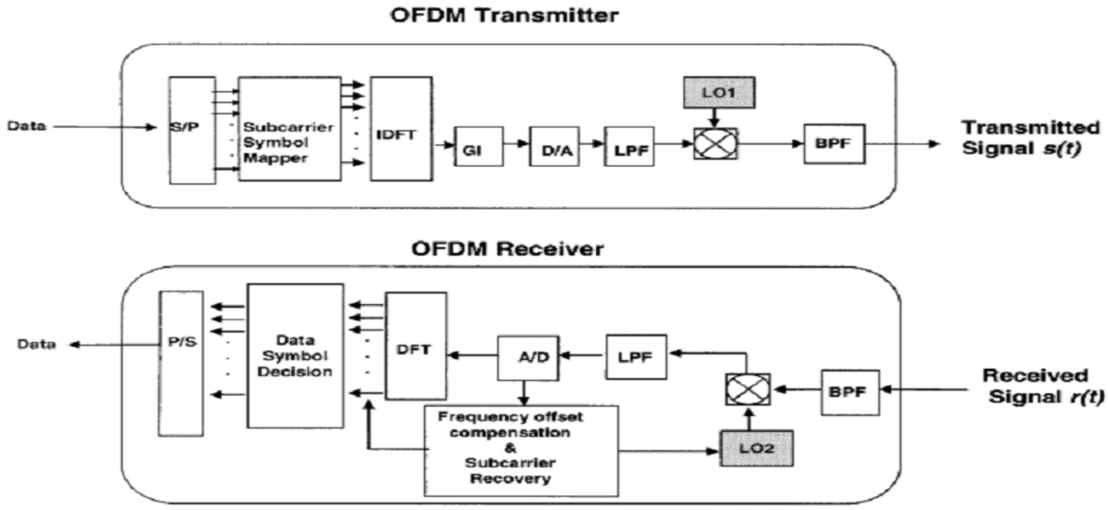


Figure II.18 Schematic designs of optical OFDM transmitters and receivers LPF, BPF, and LO stand for low-pass filter, bandpass filter, and local oscillator, respectively Ref [82]

Where $s_k(t)$ represents the kth subcarrier at frequency $f_{LO}+f_k$, Ts is the OFDM symbol duration, and h(t) = 1 in the interval 0 < t < Ts but zero outside of it. This composite signal is used to modify an optical carrier on the ITU grid at a specified frequency. All actions are reversed at the receiver end to restore the original data bit stream [23-82].To understand the origin of subcarrier orthogonality, remember that the DFT frequencies associated with a periodic time-dependent function (period Ts) are provided by f_k = (k- l)/Ts, where the number k can take any value between 1 and N. As a result, the subcarriers thus form a comb of uniformly spaced frequencies. The orthogonality of subcarriers follows from the relation [23].

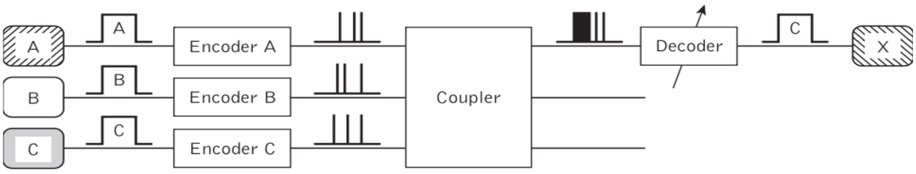
$$\left\langle s_k(t)\, s_l^*(t) \right\rangle = \frac{1}{T_s} \int_0^{T_s} s_k(t) s_l^*(t) dt = \delta_{kl} \qquad \text{(II.6)}$$

The average across the whole OFDM symbol length is shown by angle brackets. Because the input bit stream is split into N parallel streams, it is important to recall that $T_s = NT_b$, where T_b is the bit slot. N frequently surpasses 100 and sometimes approach 1000[25,28,23,80]. T_s is much longer than T_b . In other words, each subcarrier's symbol rate is B/N. We can deliver an input bit stream in the form of N symbol streams, each on its own subcarrier, using the OFDM method. Two neighboring symbol streams have a lot of overlap in their spectra. Due to the orthogonality of these subcarriers, they can still be demodulated at the receiver [81,82,83].

II.4.4 Code-Division Multiplexing (CDM)

Optical code division multiplexing (OCDM), sometimes termed optical code division multiple access (OCDMA) is a digital technique where each channel occupying a given wavelength, frequency or time slot, the information is transmitted using a coded sequence of pulses. each channel employs a different code to transmit and recover the original signal. It works on the spread spectrum principle, where all users share the fiber channel bandwidth at the same time.The basic OCDM technique is

illustrated in Fig II.19 where multiplexing of three channels is accomplished by transmitting a unique time-dependent series of short pulses. Each bit to be transmitted is subdivided into a number of small intervals n known as chips (e.g. n = 64 or 128).Each user is then assigned a unique chip sequence of the n bit code. Many coding schemes exist for the generation of the chip sequences to encode/decode OCDM channels, with the overall premise that the greater the number of unique sequences needed (i.e. number of users), the larger the code sequence required. Each bit is subdivided into a number of small intervals n known as chips (e.g. n = 64 or 128) to be transmitted. then A decoder is used at the receiving end to recover the particular channel employing autocorrelation with the original chip sequence. As each data bit is converted in many chips. However, ultra short pulses (i.e. 10^{-15} second pulse length) are necessary in OCDM systems in order to enable an expanding number of OCDM channels to be broadcast on a single fiber.
Furthermore, the larger the number of channels, the longer the code sequences needed to provide a unique channel code. Nevertheless an optical OCDM multiplexer has been reported which provided bidirectional data transmission over 100 km of single-mode fiber. In addition, an experimental test bed has successfully demonstrated both 160 and 320 Gbit s^{-1} OCDM transmission systems. These systems using signal wavelengths centered at 1.55 μm supported 16 and 32 channels, respectively, with each channel operating at a transmission rate of 10 Gbit s^{-1} [84].



FigureII.19 Block schematic showing three channels of an optical fiber code division multiplexing system

II.4.4.1 Optical codes

The use of CDMA as a multiple access technique simultaneously raises the question of the implementation of coders and the choice of code sequences to be used to distinguish the signals associated with the different transmitters(Fig II.20).The choice of codes appropriate for the realization of an optical system of multiple access by code is determined by the multiplexing capability, the size of the code sequences, their weight, the complexity of the associated detection systems, and the performance of the codes in terms of auto and inter correlation functions. Multiple access interferences, which are caused by the code sequences' intrinsic cross-correlations, are also a deciding factor in the code family to use, the kind of coders/decoders, and the detection system[85].

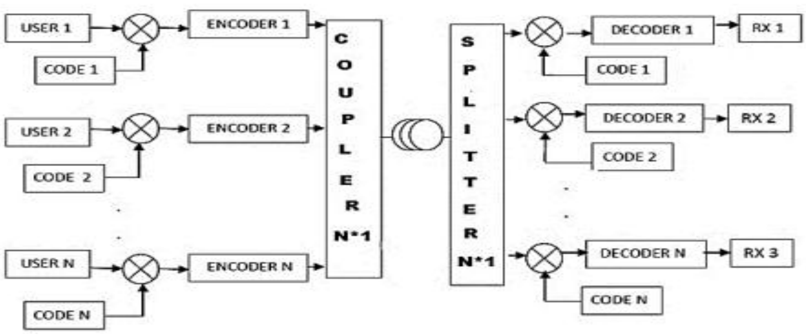


Figure II.20 OCDMA System.

Optical encoding and decoding for incoherent OCDMA uses unipolar codes whereas the bipolar codes used in RF CDMA (radio frequency code division multiple access) have poor performance in OCDMA system and can't be used. Therefore, unipolar codes with good system performance need to be developed. Consequently, in the earlier years, the research on incoherent OCDMA focused on looking for and obtaining unipolar codes with good auto-and cross correlations, such as OOC (optical orthogonal/pseudo orthogonal codes) and PC (prime codes)[84].

II.4.4.1.1 Orthogonal optical codes (OOC)

OOC are part of the family of unipolar sequences, that is to say, signals composed of pulses that can take only the two values: "1" and "0". In order to be able to distinguish between the long pulses that make up the informative signal and the shorter pulses that make up a code sequence, the former will be called 'information bits', while the latter will be called 'chips'. The OOC were developed by Salehi in 1989.OOC is determined by the length of the sequence, L, which indicates the number of chips in the sequence, the weight of the code, W, which indicates the number of level chips in a code sequence and the multiplexing capacity, N, which indicates the number of users who can be multiplexed with this sequence family.The maximum number of NOOC code sequences must satisfy the following relationship [86]:

$$N = \left\lfloor (L-1) / \left(W(W-1)\right) \right\rfloor \quad \text{(II.7)}$$

Where$\lfloor\ \rfloor$ is the operator which takes the integer portion of a lower value number,it should be noted that this theoretical expression gives an upper bound on the number of possible users in a family code.

II.4.4.1.2 Prime code (PC)

The initial version of the initial Prime Codes (PC) was introduced by Cooper and Nettleton in 1978 for applications in cellular communications, using frequency-hopping spectrum spreading techniques. The objective of these constructions is mainly to allow an asynchronous emission of the data by controlling the levels of cross-correlations that can be generated by codes of the same group. Starting in 1983, Shaar and Davis considered incorporating this type of coding into optical networks using CDMA as a multiplexing method [85]. Since this study, various studies [86] have put into perspective the development and use of these codes in various configurations of optical systems[87].

Prime Codes are generated from predefined algorithms. Their construction is therefore not exhaustive, which facilitates their generation. They also make it possible to obtain shorter sequences with a better multiplexing capacity for codes of smaller or identical size to the OOC.

PC codes, like OOC codes, are unipolar codes that allow for the multiplexing of a limited number of users while limiting the amounts of multi-user interference that occur from this multiplexing.

PC codes, like OOC, are defined by their size or length L, their weight W and their multiplexing capacity N. The peculiarity of these sequences is that their construction algorithm is based on the choice of a prime *p* number.Consider i and j as two numbers between *0* and *p-1*. A series of sequences is calculated by the equation[84]

$$\begin{cases} S_{i,j} = \left\{ s_{i,0}, s_{i,1}, \ldots, s_{i,j}, s_{i,p-1} \right\} \\ s_{i,j} = i, j \bmod (p) \end{cases} \quad \text{(II.8)}$$

The PC sequences $\boldsymbol{C_i}$ which will be used to encode and multiply the signals associated with different users, are generated by

$$c_{i,k} = \begin{cases} 1 & \text{if } \quad k=s_{i,j}+j.p \ , \ \text{for } j=\{0,1,2,...,p-1\} \\ 0 & \text{elsewhere} \end{cases} \qquad \text{(II.9)}$$

The code length and code weight of the prime code are $N=P^2$ and $W=P$ respectively. Maximum auto-correlation side lobe and maximum cross-correlation functions are $\lambda a=p-1$ and $\lambda c=2$ respectively. The cardinality of PC (The maximum number of users) $N=P$. we will refer to such Prime Code with *PC* (P^2, P).One of the specificities of this algorithm is to allow the generation of shorter codes.

Table II.2: Table gives an example of a family of PC generated by the algorithm described above, for value of $P=5$

I	S_i	C_i
0	00000	10000 10000 10000 10000 10000
1	01234	10000 01000 00100 00010 00001
2	02413	10000 00100 00001 01000 00010
3	03142	10000 00010 01000 00001 00100
4	04321	10000 00001 00010 00100 01000

II.4.4.2 Detection systems

The reception structure used at the end of the transmission chain is a very important element, whose function is to receive the signal transmitted in the optical fiber and then, from this signal, estimate the data transmitted by the desired user. Different structures of receipt may be used for OCDMA [87].
There are three structures of receiver: Conventional Correlation Receiver (CCR), CCR with Hard Limiter (HL+CCR) and Parallel Interference Cancellation (PIC).

II.4.4.2.1 Conventional Correlation Receiver (CCR)

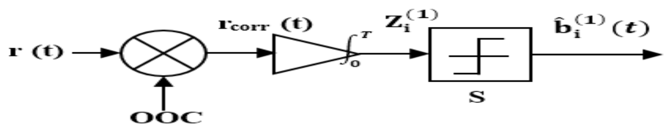


Figure II.21 Conventional Correlation Receiver (CCR)

The performance of an OCDM system can be limited by MAI(Fig II.21), by the noise of optical components and by the impairments of an optical link. In order to study MAI cancellation, we consider all optical components to be ideal, i.e. errors are only due to MAI. In this case, we obtain error probability for the CCR [87]: S: the threshold of a receiver.

$$P_{eCCR} = \frac{1}{2}\sum_{i=s}^{N-1} C_{N-1}^{i}\left(\frac{W^2}{2F}\right)^{i}\left(1-\frac{W^2}{2F}\right)^{N-1-i} \qquad \text{(II.10)}$$

II.4.4.2.2 Conventional Correlation Receiver with Hard Limiter (HL+CCR)

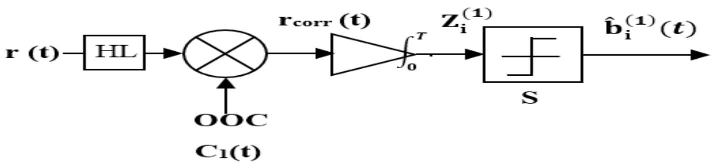


Figure II.22 Conventional Correlation Receiver with Hard Limiter (HL-CCR)

The HL-CCR reception structure presented in Figure uses the principle of the CCR; the only difference is an added function called Hard Limite (HL).The HL is an optical device that reduces received optical power. The error probability of the HL-CCR for the OCDMA system is written:

$$P_{EHL-CCR} = \frac{1}{2} C_S^W \Pi_{i=0}^{S-1}\left(1-\left(1-\frac{W^2}{2F}\right)^{N-1-i}\right) \quad \text{(II.11)}$$

II.4.4.2.3 Parallel Interference Cancellation Receiver (PIC)

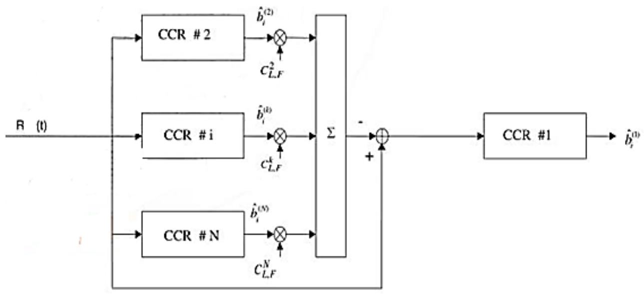


Figure II.23 Parallel Interference Cancellation Receiver (PIC)

The PIC receiver provides a simultaneous estimation of the contribution of each non-desired user. Then, an interference pattern is subtracted from the received signal before detecting, by means of a CCR, the data transmitted by the desired user (Fig II.23). We have established in [85] the theoretical expression of error probability:

$$P_{EPIC} = \left(\frac{1}{2}\right)^N \sum_{N_1=S_r-1}^{N-1} \sum_{N_2=W+1-S_F}^{N-1-N_1} C_{N-1}^{N_1} C_{N-1-N_1}^{N_2} (P_I)^{N_2} (1-P_I)^{N-1-N_1-N_2} \quad \text{(II.12)}$$

$$P_I = \frac{W^2}{F} \sum_{n_1=S_r-1}^{N_1} C_{N_1}^{n_1} \left(\frac{W^2}{F}\right)^{n_1} \left(1-\frac{W^2}{F}\right)^{N_1-n_1} \quad \text{(II.13)}$$

II.5 Conclusion

This chapter gives a short introduction to Optical LAN networks and passive optical networks, The (PONs) design was proposed as an approach to share the enormous fiber data transfer capacity among numerous clients through an aloof splitter, and subsequently improve the per client cost of optical LAN, then we studied multipexing , multiplexing is the process of combining multiple signals for transmission on a single transmission channel at the same time. The majority of transmission systems in the telecommunications network have more capacity than a single user requires. Multiplexing is the process of combining multiple signals for transmission on a single transmission channel at the same time. We also studied Channel Multiplexing Techniques, where traditional TDM (Time Division Multiplexing)-based bit rate increases are unable to meet the increasing demand for increased transmission capacity generated by data communication and the Internet. Due to the urgent need for more transmission capacity, the system planner decided to employ WDM systems rather than TDM systems to maximize the usage of existing optical fibers. WDM systems are believed to be the most cost-effective approach to deal with growing transmission capacity while still utilising existing transmission technology. where Orthogonal frequency-division multiplexing (OFDM) is a well-known multiplexing technique in the context of cell phones and other wireless applications, also we have CDMA, to recover the original signal, we must transmit each channel with a different code

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CHAPTER III

Characteristics of Optical Amplifiers

III.1 Introduction

Fiber losses unavoidably restrict the transmission distance of any fiber optic communication system[1], and in the 1980s, optical amplifiers were not commercially available, therefore long-haul fiber-optic communication systems employed electrical amplifiers to compensate for fiber loss. After electrical domain amplification, the optical signal was transformed to an electrical signal using a photodetector (O/E conversion) and then returned to the optical domain (E/O conversion). This form of optoelectronic regenerator, however, is expensive for multi-channel optical communication systems[2,1]. With the advent of optical amplifiers, the optical signal may now be amplified directly without the need for O/E and E/O conversion[1,2,3]. During the 1980s, several types of optical amplifiers were created, and their use in long-haul light wave systems became common in the 1990s. Optical amplifiers were included in fiber optic cables laid across the Atlantic and Pacific seas by 1996[1].
This chapter focuses on three types of optical amplifiers: (1) semiconductor optical amplifiers (SOAs), (2) erbium-doped fiber amplifiers (EDFAs), and (3) Raman amplifiers. Physical concepts, governing equations, noise amplifications, and practical applications are all covered in each situation. From Sections III.2 to III.6, we explore a generic amplifier and discuss the system impact of noise.In Sections III.7 to III.10, we focus on specific amplifiers.

III.2 Optical Amplifier Model

We analyze a basic amplifier model in which, as shown in Fig(III.1), the amplifier multiplies the input power by a factor of G (the amplifier's power gain) and adds white noise.. Let an amplifier's input and output be the signal field envelope ψ_{in} and ψ_{out} , respectively[2],

$$\psi_{out} = \sqrt{G}\psi_{in} + \mathrm{n} \qquad \text{(III.1)}$$

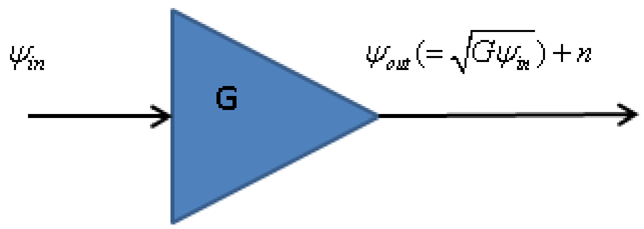

Figure III.1 Simple Amplifier model

$$P_{out} = |\psi_{out}|^2 = G|\psi_{in}|^2 = GP_{in} \qquad \text{(III.2)}$$

Noise n(t) is introduced by the amplifier and the total field envelope at the output of the amplifier is

$$\psi_{tot} = \psi_{out} + n(t) = \sqrt{G}\psi_{in} + n(t) \qquad \text{(III.3)}$$

The gain is provided by stimulated emission, while the noise is mostly caused by spontaneous emission in the amplifier. We assume that the n(t) samples are Gaussian complex random variables with equal distributions.

III.3 Amplified Spontaneous Emission in Two-Level Systems

The light wave produced by stimulated emission has the same polarization, frequency, and phase as the incident wave, but the light wave produced by spontaneous emission has a random phase and frequency and propagates in all directions. Amplified spontaneous emission (ASE) occurs when an amplifier increases spontaneously emitted photons [2,3]. ASE is the primary cause of noise in the amplifiers [3]. The mean number of photons at the output of an L-length amplifier is given by

$$n_{ph}(L) = n_{ph}(0)G + n_{sp}(G-1) \qquad \text{(III.4)}$$

Where $n_{ph}(0)$ is the mean number of photons at the amplifier input (z = 0), G is the amplifier gain, and n_{sp} is the spontaneous emission factor or population-inversion factor, given by[2]

$$n_{sp} = \frac{N_2}{N_2 - N_1} \qquad \text{(III.5)}$$

Population densities in states 1 and 2, respectively, are N_1 and N_2. Eq. (III.4) is of fundamental significance. On the right-hand side, the first and second terms reflect the photon gain due to stimulated emission and spontaneous emission. When there is full population inversion, N_1 = 0 and n_{sp} = 1. This corresponds to an ideal amplifier. For a realistic amplifier, $N_1 \neq 0$ and n_{sp} is greater than 1 [2].The mean number of photons n_{sp} $(G - 1)$ corresponds to the mean noise power P_{ASE} in the frequency range of f_0 to $f_0 + \Delta f$ in a single polarization:

$$P_{ASE,sp} = n_{sp} h f_0 (\mathrm{G}-1)\Delta f \qquad \text{(III.6)}$$

The subscript *sp* here corresponds to single polarization. The power of noise given by Eq. (III.6) is the per-mode noise energy. in a single-mode fiber, there are two modes corresponding to two polarizations . Thus, in two polarizations, the noise power is :

$$P_{ASE,\mathrm{dp}} = 2 n_{sp} h f_0 (\mathrm{G}-1)\Delta f \qquad \text{(III.7)}$$

The spectral density of power (PSD) generated by Eq(III,8) is the noise power per unit frequency interval :

$$\rho_{ASE,dp} = \frac{p_{ASE,dp}}{\Delta f} = 2 n_{sp} (G-1) h f_0 \qquad \text{(III.8)}$$

It's worth noting that Eq.(III.8) gives a single-sided PSD, with positive frequency components. The ASE can be thought of as a white noise process because the power spectral density remains constant over the bandwidth $\Delta f \ll f_0$. Per polarization, the single-sided PSD is

$$\rho_{ASE,sp} = n_{sp} h f_0 (G-1) \qquad \text{(III.9)}$$

III.4 Amplifier Noise Figure

All amplifiers reduce the signal-to-noise ratio (SNR) of the amplified signal because of spontaneous emission, which adds noise to the signal during amplification [1].The amplifier noise figure F_n is a standard way to describe the noise that an amplifier adds. It is defined as the electrical SNR at the amplifier input divided by the electrical SNR at the amplifier output [2,1].

$$F_n = \frac{(SNR)_{in}}{(SNR)_{out}} \tag{III.10}$$

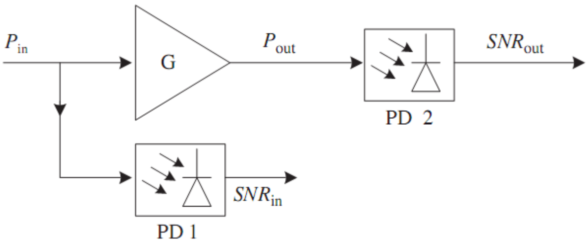

Figure III.2 Measurement of the amplifier noise figure[2]

Because $(SNR)_{out}$ can never exceed $(SNR)_{in}$, the nois figure is bigger than unity (see Fig.III.2).

Let's look at (SNR) in first. The photocurrent is when the incident power is Pin.

$$I_{in} = RP_{in} \tag{III.11}$$

Responsivity is given by Eq

$$R = \frac{\eta}{h f_0} = \frac{q}{h f_0} \tag{III.12}$$

$\eta = 1$ is assumed. The carrier frequency is f_0 in this case. The power provided by an electrical signal to a load resistor R_L is $S_{in} = I_{in}^2 R_L$ (III.13)

Therefore, we have $SNR_{in} = \frac{S_{in}}{N_{shot}} = \frac{RP_{in}}{2qB_e}$ (III.14)

Before the amplifier, we assume there is no noise in the optical signal. The shot noise causes the noise power at PD1's output, which is given by Eq.

$$N_{shot} = 2qI_{in}R_L B_e \tag{III.15}$$

Next, Consider SNR_{out}. The amplifier's output optical power is[2,4]

$$P_{out} = GP_{in} \tag{III.16}$$

As well as the photocurrent and electrical signal power that go along with it

$$I_{out} = RGP_{in} \tag{III.17}$$

$$S_{out} = (RGP_{in})^2 R_L \tag{III.18}$$

The noise power delivered to a resistor R_L consists of the shot noise and the signal–ASE beating noise.

$$N_{out} = N_{shot} + N_{s-sp} = 2qRP_{out}R_L B_e + 4R^2 \rho_{ASE} P_{out} B_e R_L \tag{III.19}$$

It should be noted that the power spectral density of the ASE noise in Eq.(III.17) is in single polarization. Despite the fact that the amplifier introduces noise in both polarizations, the noise orthogonal to the signal polarization does not interfere with it, resulting in signal–ASE beat noise. The SNR at the output of PD2 can be be expressed as

$$SNR_{out} = \frac{S_{out}}{N_{out}} = \frac{RGP_{in}}{(q + 2R\rho_{ASE})2B_e} \tag{III.20}$$

Substituting Eqs.(III.14) and (III.20) in Eq .(III.10),we find

$$F_n = \frac{RP_{in}}{2qB_e}\frac{(q + 2R\rho_{ASE})2B_e}{RGP_{in}} = \frac{q + 2R\rho_{ASE}}{Gq} \tag{III.21}$$

Using Eq.(III.12), Eq.(III.21), we find

$$\rho_{ASE} = (GF_n - 1)hf_0 / 2 = n_{sp}(G-1)hf_0 \tag{III.22}$$

The formula that connects the amplifier noise figure to the spontaneous emission factor n_{sp} is[1,2,4]

$$F_n = \frac{2n_{sp}(G-1)}{G} + \frac{1}{G} \tag{III.23}$$

When $G \gg 1$

$$F_n \cong 2n_{sp} \tag{III.24}$$

The noise figure is measured in decibels (dB).

$$F_n(dB) = 10\log_{10} F_n \tag{III.25}$$

F_n = 3dB for n_{sp} = 1, corresponding to an ideal amplifier with the lowest ASE noise[2], F_n exceeds 3dB ,and can be as large as 6–8dB[1]. An optical amplifier's *Fn* should be as low as possible for use in optical communication systems[1]

III.5 Optical Signal-to Noise Ratio

The ratio of electrical SNRs at the amplifier's input and output is the noise figure, characterizes the noise added by the amplifier. The optical signal-to-noise ratio (OSNR) can also be used to describe the noise added by the amplifier.

$$OSNR = \frac{\text{mean signal power}}{\text{mean noise power in a bandwidth of 0.1 nm}} \tag{III.26}$$

At 1550nm, 0.1nm corresponds to B_{opt} = 12.49GHz and the mean noise power in the bandwidth of B_{opt} is

$$P_{ASE} = 2\rho_{ASE}B_{opt} \tag{III.27}$$

$$OSNR = \frac{P_{out}}{P_{ASE}} \tag{III.28}$$

Or in decibels,

$$OSNR(dB) = 10\log_{10}\text{OSNR} \tag{III.29}$$

III.6 Amplifier Applications

Optical amplifiers can be used for a variety of applications in fiber-optic communication systems. in Fig.III.3, three common applications are illustrated schematically. The use of amplifiers as in-line amplifiers is the most common use for longhaul networks.Electronic regenerators are being replaced with amplifiers. as long as the device performance isn't restricted by the cumulative results of fiber dispersion, fiber nonlinearity, and amplifier noise, several optical amplifiers may be cascaded in a periodic chain [1]. Optical amplifiers are in particular attractive for WDM mild wave structures because all channels may be amplified at the identical time.any other approach to make use of optical amplifiers is to area an amplifier right after the transmitter to enhance the transmitter's energy, those amplifiers are known as power amplifiers or power boosters considering their primary function is to increase the quantity of power introduced [1]. the gap among transmitter and receiver can also be extended by means of setting an amplifier in front of the receiver to increase the received power. Optical preamplifiers are a type of amplifier this is often used to increase receiver sensitivity, Optical amplifiers can also be used to compensate for distribution losses in nearby-area networks [1].

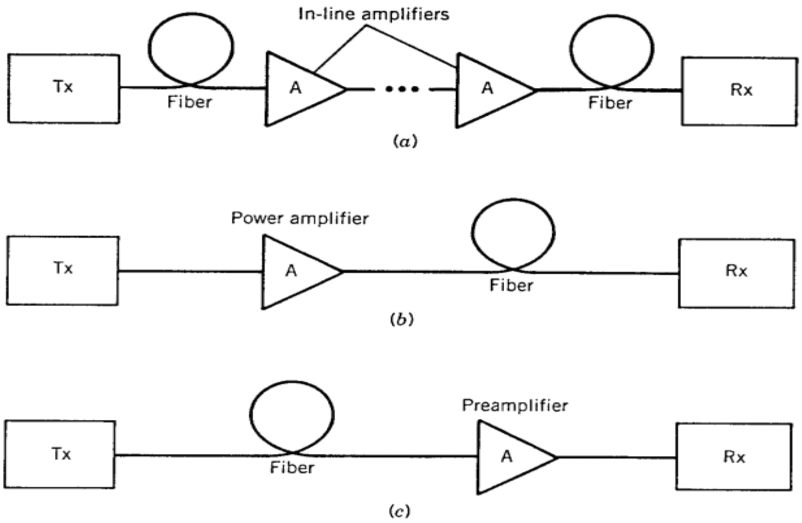

Figure III.3 Three possible applications of optical amplifiers in lightwave systems:(a)as in-line amplifiers; (b) as a booster of transmitter power ;(c)as a preamplifier to the receiver[1].

Optical amplifiers, such as semiconductor optical amplifiers (SOAs), erbium-doped fibers amplifiers (EDFAs), and Raman amplifiers, can all be used to enhance an optical signal. Fig III.4 shows typical gain profiles for different optical amplifier designs based around the 1.3 and 1.5 m wavelength regions. The semiconductor optical amplifier (SOA), the erbium-doped fiber amplifier (EDFA), and the Raman fiber amplifier all have large spectral bandwidths, as can be shown. We will talk about each of them in detail[5].

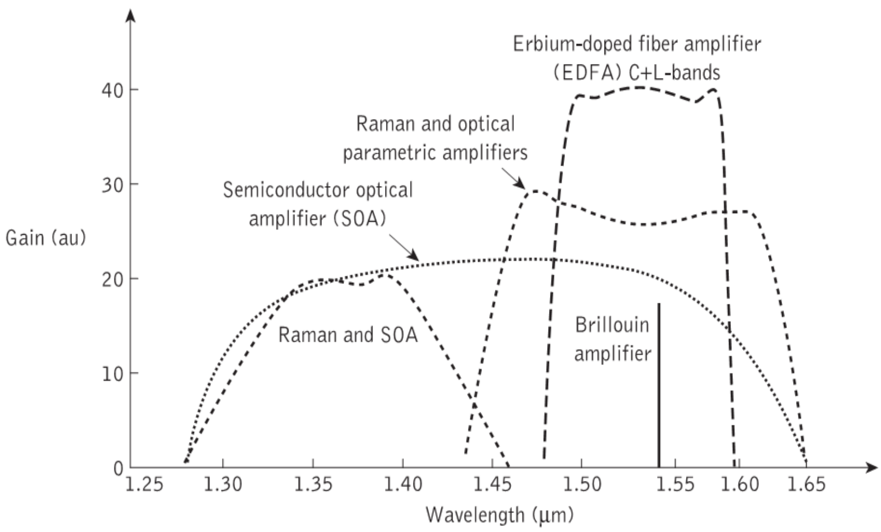

Figure III.4 Gain–bandwidth characteristics of different optical amplifiers[5]

III.7 Semiconductor Optical Amplifiers

All lasers, consisting of semiconductor lasers, act as amplifiers when they are close to but not quite at threshold [2,1]. Certainly, research on semiconductor optical amplifiers (SOAs) began shortly after semiconductor lasers were invented in 1962. but, SOAs have been now not designed for sensible purposes till the 1980s, due to its capability applications in light wave systems [2,1,6]. Semiconductor optical amplifiers can be used in each nonlinear and linear modes of operation [5]. SOAs are classified into kinds: (i) cavity-type SOAs, additionally referred to as Fabry–Perot amplifiers (FPA),and (ii) traveling wave amplifiers (TWA) [5,2,4]. The difference between these groups being the facet reflectivities [5], these devices may provide high internal gain (15 to 35dB) while consuming little power, and their single-mode waveguide construction makes them ideal for use with single-mode fiber[5]. When compared to Raman and EDFA, semiconductor optical amplifiers (SOAs) are the best options due to their compact size and low power compensation requirements [7]. Semiconductor optical amplifiers (SOAs) are simply laser diodes with fibres connected to both ends and no end mirrors. Anti-reflection coatings have been applied to the end mirrors. An anti-reflection coating is a thin-film dielectric coating that is applied to an optical surface to minimize its optical reflectivity within a certain wavelength range[8,9]. Semiconductor optical amplifiers (SOAs) have material and structural nonlinearities that can be exploited to accomplish some of the tasks required in the future all-optical networks. The rapid nonlinearities may be utilized in devices used for four-wave mixing (FWM) based applications, and the carrier density saturation can be employed in cross gain (XGM) and cross phase modulation (XPM) systems[10]. Different wavelength bands can be employed with semiconductor optical amplifiers. Although SOAs have a wide band amplification range, they have a high noise figure and a large wavelength dependant gain. As a result, they can only be used to amplify limited number of DWDM channels [11].

III.7.1 Cavity-Type Semiconductor Optical Amplifiers

Reflections at the cleaved facets (32 % reflectivity) produce a significant amount of feedback in semiconductor lasers. When biased to a low threshold, they can be utilized as amplifiers although multiple reflections at the facets must be taken into account by using a Fabry–Perot (FP) cavity, such amplifiers are called FP amplifiers[1].

Let R_1 and R_2 be the power relectivities of mirrors M_1 and M_2 , respectively, as shown in Fig III.5. The corresponding power transmittivities at mirror M_j are given by assuming that power is conserved at every mirror[2].

$$T_j = 1 - R_j \quad ; \quad j = 1, 2. \tag{III.30}$$

$$\psi_0 = \psi_{in} t_1 t_2 \sqrt{G_s} \exp(i\phi_0) \tag{III.31}$$

Where $t_1\psi_{in}$ is the optical field transmitted at A, $\psi_{in} = \sqrt{P_{in}}$, $|t_j| = \sqrt{T_j}$,j = 1 , 2 .The gain coeficient is g and the cavity internal loss is α_{int} ,the net gain coeficient is $g_s = \Gamma_g - \alpha_{\text{int}}$,where Γ is the overlap factor , after a single pass, the partial optical field is ψ_0 at B [2] .

Where $\phi_0 = 2\pi nL/\lambda$ is the propagation phase shift, n is the gain medium's refractive index, and λ is the free-space wavelength. The single-pass gain in the small-signal limit is:

$$G_s = \exp(g_s L) \tag{III.32}$$

A part of the optical field is reflected at mirror M2, which is then reflected at mirror M1. The partial field at B is completed after one round trip (see Fig IV.5)

$$\psi_1 = \psi_{in} t_1 r_2 r_1 t_2 [\sqrt{G_s}\exp(i\phi_0)]^3 \tag{III.33}$$

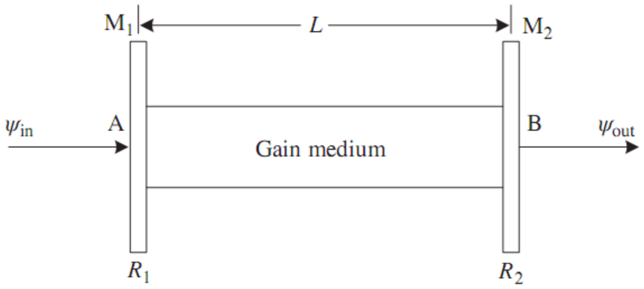

Figure III.5 Cavity-type semiconductor Optical Amplifier [2]

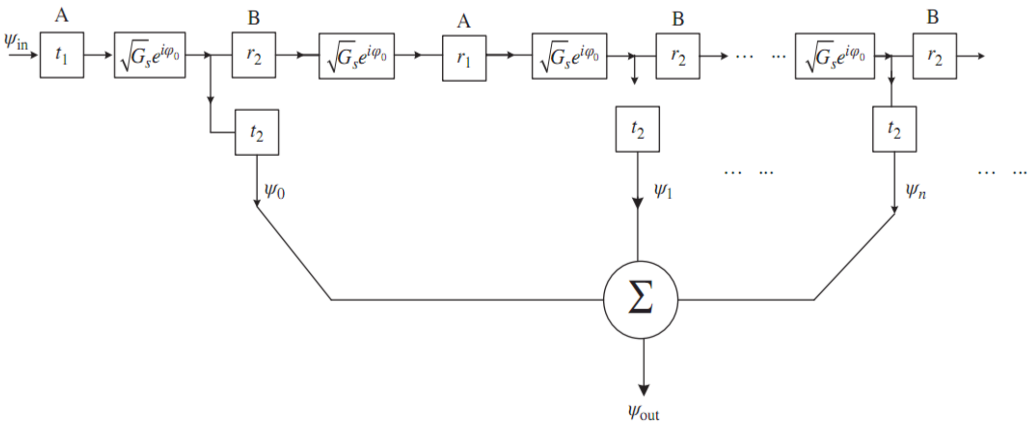

Figure III.6 The optical signal output of the amplifier is the sum of the partial flields due to repeated reflections [2]

Where $|r_j| = \sqrt{R_j}$, $j = 1, 2$. The partial field at B after j round trips is:

$$\psi_j = \psi_{in}\, t_1\, t_2\, (r_1\, r_2)^j [\sqrt{G_s}\exp(i\phi_0)]^{2j+1} \tag{III.34}$$

At B, the full field output is the sum of partial fields :

$$\psi_{out} = \sum_{j=0}^{\infty} \psi_j = t_1\, t_2\, \psi_{in} \sqrt{G_s}\exp(i\phi_0) \sum_{j=0}^{\infty} h^j \tag{III.35}$$

$$h = r_1\, r_2\, G_s \exp(i2\phi_0) \tag{III.36}$$

And if $|h| \prec 1$ we have:

$$\sum_{j=0}^{\infty} h^j = \frac{1}{1-h} \tag{III.37}$$

As a consequence, Eq.(III.35) becomes :

$$\psi_{out} = \frac{\psi_{in}\, t_1\, t_2\, \sqrt{G_s}}{1-h}\exp(i\phi_0) \qquad \text{(III.38)}$$

The overall gain G is calculated as follows by using Eq (III.36) [5,2] :

$$G(f) = \frac{|\psi_{out}|^2}{|\psi_{in}|^2} = \frac{|t_1|^2\,|t_2|^2\, G_s(f)}{[1-h(f)][1-h^*(f)]} = \frac{(1-R_1)(1-R_2)G_s(f)}{1+R_1R_2G_s^2(f)-2\sqrt{R_1R_2}G_s(f)\cos(2\phi_0)} \qquad \text{(III.39)}$$

Where:

$$\cos(2\phi_0) = 1-2\sin^2\phi_0 \qquad \text{(III.40)}$$

We find:

$$G(f) = \frac{(1-R_1)(1-R_2)G_s(f)}{(1-RG_s)^2+4RG_s\sin^2(2\pi nfL/c)} \qquad \text{(III.41)}$$

The geometric mean of facet relectivities is $R=\sqrt{R_1R}_2$, from Eq.(III.41) we can see that the peak gain occurs when (where : $m = 0, \pm1, \pm2, ...$)

$$\frac{2\pi nfL}{c} = m\pi \qquad \text{(III.42)}$$

Or:

$$f = \frac{mc}{2nL} \qquad \text{(III.43)}$$

Any input signal whose frequency is matched to the cavity's resonant frequency f_m is amplified via way of means of the cavity-kind optical amplifier.When the signal frequency equals one of the resonant frequencies, the peak gain happens is :

$$G_{peak} = \frac{(1-R_1)(1-R_2)G_s(f)}{(1-RG_s)^2} \qquad \text{(III.44)}$$

The free spectral range (FSR) is the distance between two peaks .

$$FSR = f_{m+1} - f_m = \frac{c}{2nL} \qquad \text{(III.45)}$$

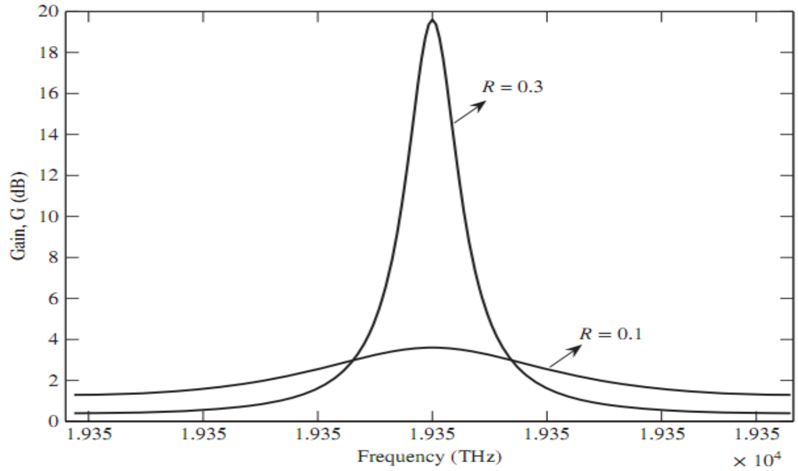

Figure III.7 Gain–bandwidth trade-off in cavity-type SOA[2]

Fig III.7 represents the gain within a free spectral range for various R values. As can be shown, the bandwidth increases as R decreases, while the peak gain decreases.

III.7.2 Traveling-Wave Amplifiers

As can be seen in Fig.III.7, the bandwidth increases as R decreases. When R = 0, Eq.(III.44) becomes G = Gs, which means the total gain is the same as the single-pass gain Gs. When R = 0, there are no partial fields due to round trips. This amplifier is referred to as a traveling-wave amplifier(TWA)[2].

From Eq.(III.41), when $\sin^2 \phi_0 = 1$,the gain is minimum ,and it is given by

$$G_{\min} = \frac{(1-R_1)(1-R_2)G_s(f)}{(1-RG_s)^2} \quad \text{(III.46)}$$

$G_{\max} = G_{peak}$,the gain ripple ΔG is :

$$\Delta G = \frac{G_{\max}}{G_{\min}} = \frac{(1+RG_s)^2}{(1-RG_s)^2} \quad \text{(III.47)}$$

In decibels,

$$\Delta G(dB) = G_{\max}(dB) - G_{\min}(dB) \quad \text{(III.45)}$$

III.8 Erbium-Doped Fiber Amplifier

Erbium-doped fber amplifer (EDFA) is generally regarded as one of the most significant optical amplifers in distributed optical fber sensors which has been able to mitigate the loss of the optical power[12 ,3,13] , because of the silica-based fiber's low-loss optical window and large gain bandwidth[14 ,13 ,15,16]. This is typically tens of nano meters (gain bandwidth) and is more than sufficient to amplify many data channels with the greatest data rates without any gain narrowing effects[14 ,17]. EDFA is an optical amplifier that amplifies an optical signal using a doped optical fiber as a gain medium. The signal to be amplified, furthermore as a pump optical laser , are multiplexed into the doped fiber, and therefore the signal is amplified by contact with the doping ions[14]. One or 2 pump lasers, co-propagating pump (forward pump) at 980 nm and counter-propagating pump (reverse pump) at 1480 nm[13,18],The EDFA bandwidth is usually the whole C band (1530 to 1565 nm). EDFAs for the L band are also available from a few manufacturers (1565 to 1625 nm).[13,18], the main disadvantage of this equipment kind is that it adds noise to the fiber link [13]. The gain-flattened erbium-doped fiber amplifier (EDFA) is an important component in long-distance multichannel lightwave transmission systems like Wavelength Division Multiplexing (WDM)[17,8,9]. In a FTTH customer access network, the EDFA is put in the optical line terminal to enhance the 1550nm light, which is utilized for video communication [8]. The discovery of erbium-doped glass fibers has sparked a lot of interest in active-fiber technology in the 1.55-μm wavelength range [19]. Er^{3+} ions are observed to have an excited state that is divided by the energy difference corresponding to a wavelength of ∼ 1530 nm from the ground state.An information-bearing signal at the carrier wavelength about 1550 nm can be amplified by stimulated emission if the population inversion is achieved. to achieve population inversion an optical pumps with a wavelength of 980 nm or 1480 nm are used , the first stage of a standard EDFA is pumped with a 980 nm source to get a low noise figure, which can create a very high degree of inversion. The EDFA's power stage is pumped at 1480 nm, resulting in a high quantum conversion efficiency [18,20]. The composition of a typical EDFA is shown in the Fig (III.8), at either 1480 nm or 980 nm, the signal to be amplified is coupled with the pump beam employing a Selective Wavelength coupling (WSC). The optical pumps are semiconductor laser diodes. At the output end, an optical isolator is used such that reflections occurring at different points along the fiber-optic transmission lines following the EDFA do not interfere with the signal within the amplifier [2], the spectrum of an EDFA is very long (30nm). EDFAs are useful in WDM systems because of their broad bandwidth[2]. An EDFA's typical gain values are around 20 to 30dB, depending on the fiber length and pump power. [3].

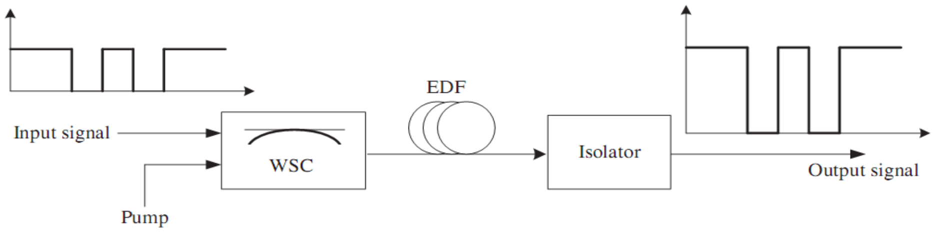

Figure III.8 Erbium-doped fiber amplifier. WSC = wavelength selective coupler, EDF = erbium-doped fiber.

Two examples of room-temperature absorption and stimulated emission spectra derived from erbium-doped silica glass fibers are shown in Fig III.9, in Fig. III.9(a) the fiber included just germanium as an index-raising codopant, but in Fig.III.9(b) the fiber contained aluminum to increase Er^{3+} solubility in glass, Adding Al additionally broadens the gain spectrum of the amplifier [19]. The loss (gain) per meter of fiber is plotted on the left y axis, while the absorption (emission) cross section is plotted on the right. A white-light source and a monochromator are used to measure loss spectra,to fully invert the Er^{3+} population to the energy level, the gain spectra are monitored with a high pump power at 980 or 528 nm. The measured loss spectrum $\alpha(\lambda)$ and gain spectrum $g^*(\lambda)$ are[19] :

$$\alpha(\lambda) = \sigma_a(\lambda)\Gamma(\lambda)n_1 \tag{III.46}$$

$$g^*(\lambda) = \sigma_e(\lambda)\Gamma(\lambda)n_1 \tag{III.47}$$

$\Gamma(\lambda)$ is the overlap integral between the optical mode and the erbium ions, and the density of erbium ions is n_1 ,$\sigma_a(\lambda)$ and $\sigma_s(\lambda)$, respectively, are the absorption and emission cross sections[19]. Analytical chemistry methods may be used to estimate n_1 in bulk glass samples, and the spectra can be determined with large optical beams where $\Gamma = 1$ .Then $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$ are immediately obtained. When n varies radially and r is unknown this technique is not applicable to fibers. Instead, the cross sections are derived in an indirect manner[19]. The Ladenburg-Fuchbauer (LF) equation is frequently used to determine the peak cross section from an integrated spectrum. One form of this equation is [19]:

$$\sigma_{a,e}(\lambda) = \frac{\lambda^4_{a,e,peak} I_{a,e}(\lambda)}{8\pi c n^2 \tau \int I_{a,e}(\lambda) d\lambda} \tag{III.48}$$

Where the wavelength at the absorption (emission)peak is $\lambda_{a,e,peak}$, the lifetime of the metastable level is τ , the refractive index of the glass is n , c is the velocity of light, and the absorption or fluorescence spectrum is $I_{a,e}(\lambda)$.

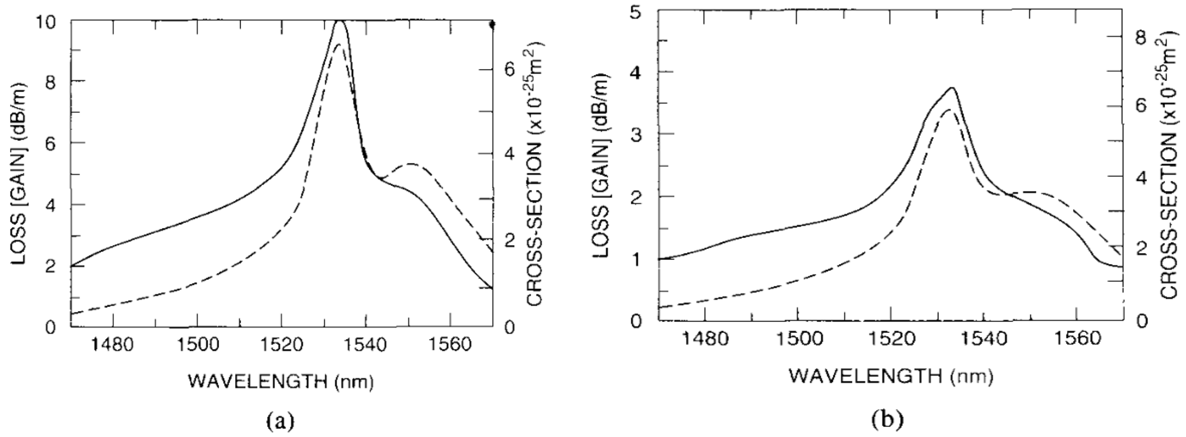

Figure III. 9 Absorption (—) and gain (---) spectra of (a) Ge: silicate and (b) A1 : Ge : silicate amplifier fibers[19].

III.8.1 Physical Principle of EDF Amplification

When Erbium is illuminated with light energy at an applicable wavelength (either 980nm or 1480nm), it's excited to a long-lived intermediate state (see Fig III.10), once that it decays to the bottom state by emitting light within the 1525-1565 nm band. If there is already light energy within the 1525-1565nm band, once a signal channel passes through the EDF[21,19], for example, it activates the decay method (stimulated emission), resulting in more light energy. If a pump wavelength and a signal wavelength are both propagating via an via an EDF at an equivalent time, energy are transferred from the pump wavelength to the signal wavelength through the Erbium, resulting to signal amplification[2,20].

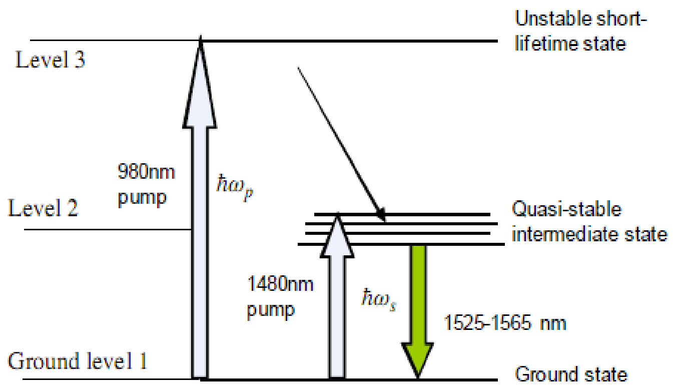

Figure III.10 The energy levels of the Erbium with the EDFA

Transitions from level 1 to level 3 are caused by an optical pump beam of frequency ω_p , Let N_j be the population densities at level j, with j = 1, 2, and 3, erbium ions excited to level 3 relax to level 2 by spontaneous emission and non-radiative processes, the signal amplification is caused by the stimulated emission that occurs between levels 2 and 1. Let τ_{jk} be the lifetime of spontaneous emission and non-radiative processes for any two levels j and k. Evaluate the level 3 gain and loss rates first., the population density of level 3 increases because of the net absorption of pump photons, while it decreases due to non-radiative emission[2,3].

$$\frac{dN_3}{dt} = R_{abs} + R_{stim} + R_{nr} + R_{sp} \quad \text{(III.49)}$$

We have R_{abs} the rate of absorption:

$$R_{abs} = B_{13}\ N_1\ u_p = B_{13}\ N_1\ \frac{I_p}{\upsilon} \quad \text{(III.50)}$$

Where is the energy density of the pump is u_p, I_p the pump intensity, and υ the speed of light in the medium.A light wave of energy E_p ,the optical intensity is :

$$I_p = \frac{E_P}{A\,\Delta_t} = \frac{n_p\hbar\ \omega_p}{A\,\Delta_t} \quad \text{(III.51)}$$

ω_p is the frequency of the pump wave, where $\hbar = h/(2\pi)$, h = Planck's constant = 6.626 × 10^{-34} J. The photon flux density ϕ_P is if n_p photons cross the region A over the time interval Δ_t

Using Eq (III.51)

$$\phi_p = \frac{n_p}{A\,\Delta_t} = \frac{I_p}{\hbar\ \omega_p} \quad \text{(III.52)}$$

We find:

$$R_{abs} = \sigma_{13} N_1 \phi_P \quad \text{(III.53)}$$

Where:

$$\sigma_{13} = \frac{\hbar\ \omega_p B_{13}}{\upsilon} \quad \text{(III.54)}$$

The absorption cross-section associated with the transition from level 1 to level 3 is σ_{13}. The following is the physical sense of the optical power absorbed by an erbium ion is proportional to the incident light wave's optical intensity I_p .

$$P_{abs} = k\ I_p \quad \text{(III.55)}$$

$$\frac{P_{abs}}{\hbar\omega_p} = \frac{kI_p}{\hbar\omega_p} = k\phi_p \quad \text{(III.56)}$$

The number of photons absorbed per unit time by an erbium ion (photon absorption rate) is $P_{abs}/\hbar\omega_p$ and ϕ_p is the photon flux density, k is a proportionality constant that depends on the medium. The overall absorption rate is calculated as follows:

$$R_{abs} = kN_1\phi_p \quad \text{(III.57)}$$

In the ground state, there are N_1 erbium ions per unit volume .From level 3 to level 1, the stimulated emission rate is given by

$$R_{stim} = -\sigma_{31} N_3 \phi_p \quad \text{(III.58)}$$

The transition from level 3 to level 2 is generally non-radiative, absorption and stimulated emission between level 3 and level 2 may be neglected..Using Eq(III.49)

$$\frac{dN_3}{dt} = (\sigma_{13}N_1 - \sigma_{31}N_3)\phi_p - \frac{N_3}{\tau_{32}} \quad \text{(III.59)}$$

$$\frac{dN_2}{dt} = N_1\sigma_{13}\phi_p - \frac{N_2}{\tau_{21}} - (N_2\sigma_{21} - N_1\sigma_{12})\phi_s \quad \text{(III.60)}$$

$$\frac{dN_1}{dt} = (N_2\sigma_{21} - N_1\sigma_{12})\phi_s - N_1\sigma_{13}\phi_p + \frac{N_2}{\tau_{21}} \quad \text{(III.61)}$$

Where :

$$R_{pump} = N_1\sigma_{13}\phi_p \quad \text{(III.62)}$$

The erbium ions absorb pump photons to make an upward transition to level 3 from level 1, then relax to level 2 through non-radiative processes. When the population is inverted $(\sigma_{21}N_2 \succ \sigma_{12}N_1)$, the pump's energy is passed to the signal.Adding Eqs.(III.60) and (III.61), we find :

$$\frac{d(N_1+N_2)}{dt} = 0 \quad \text{or} \quad N_1+N_2=N_T \quad \text{(a constant)} \quad \text{(III.63)}$$

The erbium ion density is denoted by N_T , Eqs. (III.60) and (III.61) have a steady-state solution that may be achieved by setting

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = 0 \quad \text{(III.64)}$$

Under steady-state conditions, we obtain

$$N_2 = \frac{N_T[\sigma_{13}\phi_P + \sigma_{12}\phi_s]\tau_{21}}{1+\sigma_{13}\tau_{21}\phi_p + (\sigma_{12}+\sigma_{21})\phi_s\tau_{21}} \quad \text{(III.65)}$$

$$\phi_p = \frac{\mathrm{I}}{\hbar\omega_p} = \frac{p_p}{A_{eff}\hbar\omega_p} \quad \text{(III.66)}$$

Where ϕ_p is the photon flux density and the optical power is P_p. Where the cross-section of the erbium ion distribution is A_{eff} . In a similar vein:

$$\phi_s = \frac{P_s}{A_{eff}\hbar\omega_s} \quad \text{(III.67)}$$

Substituting Eqs.(III.67) and (III.66) in Eq.(III.65),we obtain

$$N_2 = \frac{N_T[P_s^{'} + P_p^{'}]}{1+P_p^{'} + P_s^{'}(1+n)} \quad \text{(III.68)}$$

$$P_s^{'} = \frac{P_s}{P_s^{th}} \quad , \quad P_p^{'} = \frac{P_p}{P_p^{th}} \quad , \quad \eta = \frac{\sigma_{21}}{\sigma_{12}} \quad \text{(III.69)}$$

$$N_1 = \frac{N_T\eta P_s^{'}}{1+P_p^{'} + P_s^{'}(1+\eta)} \quad \text{(III.70)}$$

Where Ps and Pp are threshold powers given by

$$P_s^{th} = \frac{A_{eff}\hbar\omega_s}{\sigma_{12}\tau_{21}} \quad , \quad P_p^{th} = \frac{A_{eff}\hbar\omega_p}{\sigma_{13}\tau_{21}} \quad \text{(III.71)}$$

The signal beam's evolution is comparable to that of a semiconductor laser due to stimulated emission, absorption, and scattering.

$$\frac{dP_s}{dz} = \Gamma_s g_s P_s - \alpha_s P_s \qquad \text{(III.72)}$$

$$g_s = N_2\sigma_{21} - N_1\sigma_{12} \qquad \text{(III.73)}$$

The overlap factor is Γ_s, which accounts for how much of the signal's optical mode cross-section overlaps with the erbium ion transverse distribution profile. At the signal wavelength, α_s is the internal loss coeficient of the erbium-doped fiber. Similarly, we have :

$$\frac{dP_p}{dz} = \Gamma_p g_p P_p - \alpha_p P_p \qquad \text{(III.74)}$$

$$g_P = -N_1\sigma_{13} \qquad \text{(III.75)}$$

The pump power is attenuated since g_p is negative, whereas g_s might be positive, indicating signal amplification. We get Eq(III.75). by using Eqs. (III.66) and (III.70) in Eqs. (III.72) and (III.73).

$$g_p = \frac{-N_T\sigma_{13}[1+\eta P_s^{'}]}{1+P_p^{'}+P_s^{'}(1+\eta)} \qquad \text{(III.76)}$$

$$g_s = \frac{N_T\sigma_{12}[\eta P_p^{'}-1]}{1+P_p^{'}+P_s^{'}(1+\eta)} \qquad \text{(III.77)}$$

Eqs. (III.72) and (III.74) create a linked nonlinear differential equation that determines the increase of signal and pump powers in the EDFA, along with Eqs. (III.76) and (III.77). the signal is weak and the pump is strong when $P_s(z) \ll P_s^{th}$ and $P_p(z) \gg P_p^{th}$ at any z, Eqs.(III.72) and (III.74) can be used to get the modest signal gain. In these conditions, Eq.(III.77) is reduced to

$$g_s = N_T\sigma_{12}\eta \qquad \text{(III.78)}$$

And from Eq.(III.72) we have

$$P_s(L) = P_s(0)\exp[(\Gamma_s N_T\sigma_{12}\eta - \alpha_s)L] \qquad \text{(III.79)}$$

Typically, signal power grows exponentially with distance if $\alpha_s \ll \Gamma_s N_T\sigma_{12}\eta$.

III.8.2 Amplified Spontaneous Emission

Erbium ions can also transition to the ground state spontaneously and produce radiation at the upper energy level [3], this radiation may be seen over the full fluorescent band of erbium ion emission and travels both forward and backward down the fiber. The spontaneous emission created at any point along the fiber, like the signal, can be amplified as it propagates along the population-inverted fiber[3],the resultant radiation is known as amplified spontaneous emission (ASE), this ASE, which has nothing to do with the signal traveling through the amplifier, is the primary cause of noise in optical amplifiers[13,3].

When amplifed spontaneous emission (ASE) noise is introduced to the signal during the amplifcation process, the signal to noise ratio (SNR) at the amplifer output decreases [12].In the excited state, Er^{3+} ions emit photons spontaneously. As they propagate along the fiber, these photons become amplified, leading to ASE. The population density of the excited level is depleted because of the ASE, and the amplifier gain decreases. The fiber-loss coeficient in EDFA is much smaller than the gain coeficient g [2].

$$n_{sp} = \frac{\sigma_{21}N_2}{\sigma_{21}N_2 - \sigma_{12}N_1} \tag{III.80}$$

To determine the ASE power, Eq.(III.72) must be solved numerically because the population densities N2 and N1 vary along the fiber length. An EDFA's noise figure ($\approx 2n_{sp}$) is typically in the 4–8 dB range.Spontaneous emission occurs in all directions at random [2]. The superposition of the guided mode and radiation modes of the erbium-doped fiber can be used to express the optical field due to spontaneous emission [2]. The radiation modes are absorbed by the cladding and have no effect on the system's functioning. Similarly, the system performance is unaffected by the ASE propagating as a guided mode in the backward direction. However, backward-propagating ASE and radiation modes degrade the amplifier's performance because the ASE reduces the amplifier's gain [2].

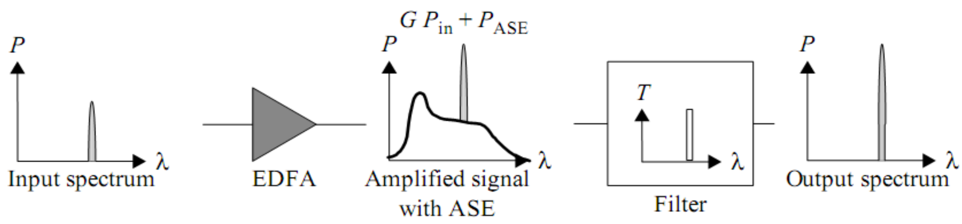

Figure III. 11 An EDFA amplifies and input signal [2]

The Fig III.11 shows the spectrum at the input and output of an EDFA. We have both the amplified signal and a background ASE at the output. An optical filter can be used to filter the ASE that appears in a wavelength region that is not coincident with the signal, as illustrated in the Fig III.11 On the contrary , The ASE that emerges in the signal wavelength region cannot be separated and comprises the amplifier's lowest added noise [3].

III. 9 Raman Amplifiers

The most significant optical amplifiers are erbium-doped fiber amplifiers, which we described. Because EDFAs operate on the basis of population inversion between erbium ion energy levels, the wavelength range that may be amplified by one is limited. Current EDFAs operative within the C-band (1530 to1565nm) and also the L-band (1565to1625nm) are available commercially. [3], some EDFA designs in the S-band (1460-1530nm) will also be available soon[3].EDFAs cannot function in other bands, thus alternative amplifiers based on other dopants (instead of erbium) and other materials (semiconductor optical amplifiers) must be sought. [3], Raman fiber amplifiers (RFAs) are amplifiers falling in the last category[3]. The Raman amplifier has less gain than an EDFA amplifier and is typically much more costly [13],it may be of interest to mention that on February 28,1928, Raman and K.S. Krishnan observed the “Raman effect” which they called the “new scattered radiation.” Raman made news paper announcements on February 29 and on March 8,1928, he communicated a paper entitled “A Change Of Wavelength in Light Scattering” to Nature; the paper was published on April 21,1928 , despite the fact that he admitted in the article that the observations were made by both Krishnan and him, the study was written by Raman, and the phenomenon became known as the Raman effect., Raman and Krishnan co-authored a number of articles. In 1930, Raman was awarded the Nobel Prize for "his work on light scattering and the discovery of the effect named after him."[3].

Raman amplification in optical fibers in the early 1970s is demonstrated by Stolen and Ippen[6]. However, during the 1970s and the early half of the 1980s raman amplifiers remained essentially laboratory curiosities. Many research articles published in the mid-1980s explained the promise of Raman amplifiers, but by the late 1980s, erbium-doped fiber amplifiers (EDFAs) had mostly surpassed them[21,23]. However, in the mid-to-late 1990s there was a resurgence of interest in Raman amplification, by the early 2000s, almost every long-haul (usually defined as 300 to 800 km) or ultralong-haul (usually defined as more than 800 km) fiber optic transmission system included Raman amplification [21,24]. Raman amplifiers square measure employed in nearly all new long-haul and ultralong-haul fiber-optic transmission systems, making them one of the first widely commercialized nonlinear optical devices in telecommunications [21], distributed Raman amplifiers have become a viable alternative to EDFAs because of its lower ASE [2].

Raman amplifiers have become viable and practicable as a result of several technological advances in recent years. The availability of upper Raman gain fibers with low loss was the key evelopment. Commercial dispersion compensating fiber, for example, has a gain efficiency that is more than ten times that of normal single-mode fiber (SMF). And the availability of all fiber elements to exchange bulk optics could be a third key technological advancement for Raman amplifiers. Gratings, wavelength-division multiplexers (WDMs), specialty couplers, and other components are now readily accessible for splicing into any fiber configuration[21]. The gain spectrum of a RAMAN amplifier depends on the pump wavelength(s), pump (s) power and the direction of pumping (forward, backward or combination)[11,25].

III.9.1 Physical Principle of Raman Amplifiers

Stimulated Raman scattering(SRS) is used by Raman amplifiers, which happens at high powers in fibers[2,1,26]. Due to SRS, associate optical wave of low frequency ω_s is made as associate intense pump beam of frequency ω_p propagates down the fiber. Stokes' shift is defined as the frequency difference $\omega_p - \omega_s = \Omega$. When a signal field of frequency ω_s (Stokes wave) is incident at the fiber's input along with the pump beam, SRS amplifies the signal field [2,1]. As shown in Fig.III.12, the pump photons cause transitions to the excited level three from level one, and silica molecules relax to one of the vibrational levels in band 2; the energy distinction $\hbar(\omega_p - \omega_s)$ seems as molecular vibrations or optical phonons. If there is a signal photon with an energy difference between level three and one of the levels in band two, the moleculesare induced to come up with signal photons of a similar kind, leading to signal amplification, additionally referred to as SRS[2]. Spontaneous Raman scattering is the source of noise in Raman amplifiers whether or not the signal beam is present where the silica molecule could switch from level 3 to band 2 [2]. Band 2 is a collection of silicon molecule vibrational states. In other words, a portion of the pump energy is turned in to signal energy, while the remainder is dissipated as molecular vibrations. Quantum mechanically, a pump photon of energy $\hbar\omega_p$ is annihilated to create a signal photon of lower energy $\hbar\omega_s$ and an optical phonon of energy $\hbar\Omega$[2]. Fig.III.13 shows the typical Raman gain spectrum for a silica-core single-mode fiber as a function of frequency shift. The frequency shift displayed in Fig.III.13 refers to the Stokes wave's frequency divergence from the pump. Around a frequency shift of roughly 14THz, the

Raman gain curve peaks[2]. Molecular vibrational states create a continuum in amorphous materials like fused silica, as seen by crossed lines in Fig.III.13, and Raman gain occurs throughout a wide frequency range up to 40THz[2].

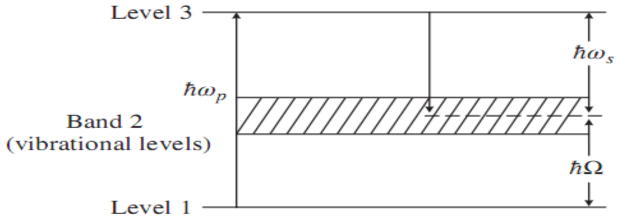

Figure III.12 Energy levels of silica [2,21]

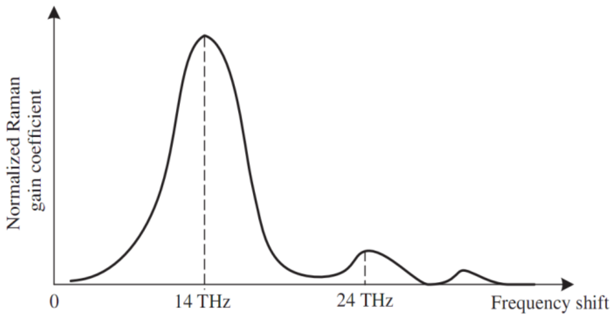

Figure III.13 Typical Raman gain spectrum of silica fibers[2,21]

The Raman amplifier with co-propagating pump is shown in Fig III.14 , a fiber coupler device is employed to combine the signal and the pump, and also the combined signal is then launched into the fiber,to provide the greatest gain for a signal wavelength of 1550 nm (corresponds to 194 THz), the pump wavelength should be around 1450 nm (corresponds to 207 THz corresponding to a frequency difference of about 14THz), in each case the pump frequency is more than the signal frequency of about 13 THz [2,3,20]. In practical systems multiple pumps utilized to ensure gain flatness over a broad range of signal frequencies[2].

The pump beam in Raman amplifiers will move into the same direction as the signal or in the opposite direction[3].Raman amplifier with counter-propagating pump (backward pumping) is shown in Fig III.15, when compared to a co-propagating scheme (forward pumping)[2,3,26], A counter-propagating pump approach has the benefit of reducing the transmission of power luctuations from the pump to the signal[2], and the lifetime associated with silica's excited state is in the region of 3 to 6 fs(femtosecond (10^{-15} s)). Because of the short lifetime, the transfer of power from the pump to the signal is virtually instantaneous, resulting in the transfer of pump luctuations to the signal [2]. If the pump is counter-propagating, the interaction time is equal to the transit time(= fiber length/speed of light)across the fiber, which is the effective life time. The transit time for an 80-km fiber length is around 0.4 ms, which is substantially longer than the real life time(in the range of femtoseconds)[2],; hence, the pump lasers in a co-propagating pump system must be extremely quiet. with very low intensity fluctuations.Both co-propagating and counter-propagating pumps are used some light-wave systems [2]. Distributed and lumped are two types of Raman amplifiers, the existing transmission fiber is employed as a gain medium in distributed Raman amplifiers, whereas a dedicated short-span fiber is employed in lumped Raman amplifiers. Typically,The lumped amplifier usually has a length of less than 15 kilometers[2], A highly nonlinear fiber with a imited effective area can be employed to maximize the pump intensity (=power/area)and gain when using lumped amplifiers, in the case of a distributed Raman amplifier, on the other hand, because nonlinear effects are amplified in small-effective-area fibers, the fiber parameter cannot be optimized to produce maximum gain ,resulting in performance degradation[2].

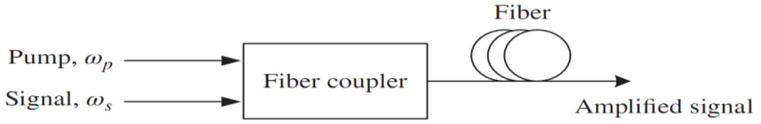

Figure III.14 Schematic of the Raman amplifier.The pump co-propagates with the signal[2]

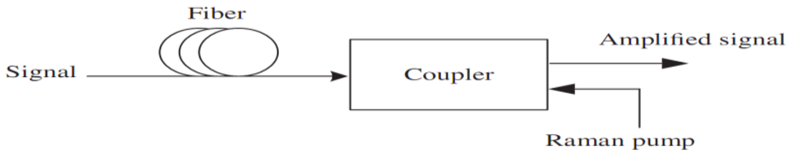

Figure III.15 Schematic of the Raman amplifier in which the pump is counter-propagating[2]

III.9.2 Governing Equations

Because of the lengthy fiber length required for Raman amplifiers, the effects of fiber losses must be factored in[1] , for the forward-pumping system the evolution of pump powers and signal is dictated by assuming pump beams and the signal are CW[2,1].

$$\frac{dP_s}{dz} = \frac{g_R P_P P_s}{A_p} - \alpha_s P_s \qquad \text{(III.81)}$$

$$\frac{dP_p}{dz} = -\frac{\omega_p}{\omega_s}\frac{g_R P_p P_s}{A_s} - \alpha_p P_p \qquad \text{(III.82)}$$

The Raman gain coefficient is g_R , the subscripts p and s denote the pump and the signal, respectively, α , P ,and A denote the loss coeficient ,the power , and effective cross-section , respectively. In order to calculate the amplifier gain, these equations must be solved numerically. However, we can gain more insight if we use the undepleted pump approximation. The depletion of the pump owing to the transfer of power to the signal is ignored in this approximation[2,1], and the solution of Eq.(III.81) is

$$P_p(z) = P_p(0)\exp(-\alpha_p z) \qquad \text{(III.83)}$$

Using Eq.(III.82) instead of Eq (III.81) , we obtain

$$\frac{dP_s}{P_s} = \frac{g_R P_p(0)\exp(-\alpha_p z)}{A_P} - \alpha_s \qquad \text{(III.84)}$$

When we integrate Eq.(III.84) from 0 to L, we get

$$P_s(L) = P_s(0)\exp\left[\frac{g_R P_p(0) L_{eff}}{A_p} - \alpha_s L\right] \qquad \text{(III.85)}$$

Where:

$$L_{eff} = \frac{1-\exp(-\alpha_p L)}{\alpha_p} \qquad \text{(III.86)}$$

The length of the effective fiber (L_{eff}) across which the pump power is significant, where G is the gain of a Raman amplifier:

$$G = \frac{P_s(L)}{P_s(0)\exp(-\alpha_s L)} = \exp\left[\frac{g_R P_p(0) L_{eff}}{A_p}\right] \tag{III.87}$$

When $\alpha_p L \gg 1$, $L_{eff} \approx 1/\alpha_p$ and Eq (III.87) can be approximated as

$$G \approx \exp\left[\frac{g_R P_p(0)}{A_p \alpha_p}\right] \tag{IV.88}$$

The gain grows exponentially as the pump's launch power rises, and it is unaffected by fiber length (when $\alpha_p L \gg 1$) [2,1].

The evolution of signal and pump powers is given by Eq(III.89)for the backward-pumping scheme :

$$\frac{dP_s}{dz} = \frac{g_r}{A_P} P_P P_s - \alpha_s P_s \tag{III.89}$$

$$-\frac{dP_P}{dz} = -\frac{\omega_P}{\omega_s}\frac{g_R}{A_s} P_P P_s - \alpha_P P_P \tag{III.90}$$

Under the undepleted pump approximations , the pump is injected at z = L where the pump power $P_p(L)$ is known, the solution of Eq.(III.90) by ignoring the first term on the right-hand side of Eq.(III.90) is

$$P_p(z) = P_P(L)\exp[-\alpha_P(L-z)] \tag{III.91}$$

Under the undepleted Pump approximations,the gain for the forward-and backward-pumping scheme is the same.

III.9.3 Noise Figure

Spontaneous Raman scattering happens at random throughout the amplifier's bandwidth and spontaneous emission photons are amplified by SRS. Since a Raman system behaves as a very inverted system with the ground-state population density $N_1 \approx 0$, the spontaneous emission factor, n_{sp}, is approximately unity[2] , As a result, the Raman amplifier's noise figure is close to 3dB, whereas the EDFA's is generally in the range of 4 to 8 dB. The OSNR of distributed Raman amplifiers is greater than that of lumped amplifiers like EDFA due to the dispersed nature of the amplification [2].

III.9.4 Rayleigh Back Scattering

The most common causes of noise in Raman amplifiers is Double Rayleigh back scattering (DRBS). Consider a distributed Raman amplifier with a signal traveling forward and ASE propagating backward, as illustrated in Fig.III.16(a). As a result of the microscopic non-uniformity in the silica composition, ASE is reflected and interferes with the signal, resulting in performance deterioration. Back scattering by a single Rayleigh particle is known as single Rayleigh back scattering (SRBS). As seen in Fig.III .16(b), the ASE and the signal are both traveling in the forward direction. A scatterer reflects the ASE backwards, and another scatterer reflects it backwards[2]. As a result, the signal and ASE are now propagating forward. The DRBS is used for ASE and also for data-modulated signals[2].

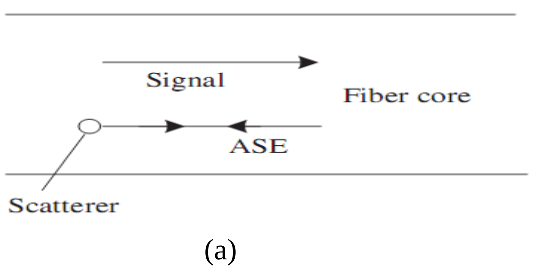

Figure III.16 (a) Single Rayleigh back scattering (b) Double Rayleigh back scattering[2].

III.9.5 Advantages and disadvantage of Raman amplifiers

Raman amplifiers have a number of key advantages. Where Raman gain is present in every fiber, allowing for a cost-effective upgrade from the terminal ends, and the gain is nonresonant, which means it is available across the whole transparency zone of the fiber, which ranges from around 0.3 to 2µm. The gain spectrum of Raman amplifiers may be adjusted by modifying the pump wavelengths, which is the third advantage [21]. Another benefit of Raman amplifiers is that it is a broad-band amplifier with a bandwidth of >5THz and a gain that is generally flat over a wide wavelength range [21]. Raman amplification refers to the capacity to amplify signals in any wavelength band utilizing any type of fiber and an appropriate pumping technique[23,24]. They do not necessitate the use of special dopants. As a result, regular, transparent, passive optical fibers can be turned into Raman amplifiers[24]. Raman gain has a fast response time. As a result, in high bit rate systems, the full bit stream may be amplified in fiber without any distortion [24].

Raman amplifiers, on the other hand, have faced a variety of problems that have hampered their use in the past. First, when compared to EDFAs, at lower signal powers they have a lower pumping efficiency [21]. Second, Raman amplifiers necessitate a fiber with a longer gain. However, in a single fiber when combining gain and dispersion compensation, this disadvantage can be overcome. An other drawback of amplifiers is their quick response time, which introduces new sources of noise. Finally, there are issues about nonlinear penalty in the WDM signal channels amplifier [21].

III. 10 Comparison between Optical Amplifiers

The underlying concept of all optical amplifiers is nearly identical, but their use in a specific application is determined by the features and restrictions listed in Table 1[7]. The EDFA and Raman add expense to the system since they require a lot of pump power to function, whereas the SOAs just need a 50mA electrical bias supply [7].

Table III .1: **Comparison between Optical Amplifiers [7]**

Feature	EDFA	SOA	Raman
Wavelength of operation	1525 to 1565 nm	Any (but limited to<50 nm bandwidth)	Any ,depend on pump wavelength and power
Gain bandwidth	10to 40 nm	20 to 50 nm	20 to 50 nm
Noise	Low	Low	Very Low
Directions	Unidirectional and bidirectional	Unidirectional and bidirectional	Unidirectional and bidirectional
Polarization sensitivity	0 Db	>few mw	0 Db
Optical pump wavelength	980 ,1400 to 1500 nm	NA	Stoke shift below signal
Optical pump power	20 to 50 mw	NA	100 to 500 mw

III .11 Conclusion

Fiber losses eventually restrict the transmission distance of any fiber optic communication system. The optical signal can be amplified directly without O/E and E/O conversion.Optical amplifiers with the advent of optical amplifiers, operate solely in the optical domain, to enable linear amplification of the transmitted optical signal, optical amplifiers are positioned at regular intervals throughout a fiber link. In theory, the optical amplifier provides a considerably simpler solution because it is a single in-line component that can be used for any type of modulation at virtually any transmission rate. Furthermore, such a device can be bidirectional, and if it is sufficiently linear, it may be able to multiplex numerous signals at various optical wavelengths (i.e. wavelength division multiplexing).
A semiconductor optical amplifier (SOA) is nothing but a laser operating slightly below threshold. The optical field incident on one facet is amplified at the other accompanied by the ASE, One disadvantage of SOAs is their polarization sensitivity. Another drawback of SOAs for WDM systems is the presence of interchannel cross-talk.While Erbium doped fibers (EDFs) are silica optical fibers that have been doped with erbium. It has been discovered that Er^{3+} ions have an excited state that is separated from the ground state by an energy difference corresponding to a wavelength of 1530nm, and therefore an information-bearing signal at the carrier wavelength around 1550 nm can be amplified by stimulated emission if the population inversion is present. Typically, optical pumps with wavelengths of 980 nm or 1480 nm are employed to induce population inversion. Because of the circular symmetry of the fiber, fiber amplifiers such as EDFA give an uniform gain for x- and y-polarization components. where distributed Raman amplifiers have emerged as a potential alternative to EDFAs Because of its reduced ASE, Raman amplifiers are based on stimulated Raman scattering, which occurs at high power levels in fibers. Raman amplifiers are used in nearly all new long-haul and ultralong-haul fiber-optic transmission systems, making them one of the first extensively commercialized nonlinear optical devices in telecommunications. with The gain bandwidth is more than 40THz wide, with the main peak located at 13.2 THz.

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CHAPTER IV

Results and Discussions

IV .1 Introduction

The proposed WDM-PONs variants, so as many of the proposals are technically interesting , and the cost and bandwidth per user, splitting ratio and maximum reach, are the dominant criteria for commercial success, are classified by choosing one option from the categories below: [1, 2, 3]

- Wavelength routed *vs* Broadcast + select (splitter PON with wavelength- selective ONUs);
- Dedicated upstream (downstream) *vs* Shared upstream (downstream);
- Cascaded optics *vs* Single-stage optics in remote node;
- Sub-carrier modulation *vs* direct modulation;
- OOK/FSK *vs* Modulation for colorless ONUs: OOK;
- Amplified (booster/pre-amplifier *vs* remotely pumped amplifiers) *vs* Un-amplified ones;

However, WDM optical networks (WDM-ONs) are used in telecommunications infrastructures, where they play a major role in the internet and future generation networks: the key factor to introduce good data transmission rates and large bandwidths [4]. Transmitting optical signals over optical networks (ONs) is often accompanied by losses due to the dispersion and non-linearity effects [5] . Erbium doped fiber amplifiers (EDFA) are the widely amplifiers that PONs have used and optical telecoms have benefited from to predict and improve system performance [6]. On another hand, the passive optical network (PON) are considered as one of the most successful access architecture that can provide high capacity and long reach by implementing optical fiber. Many PON systems use different modulation schemes, such as Time Division Multiplexing (TDM) and WDM [7-8]. TDM uses a single wavelength, delivering more channels with modest bandwidth at reasonable cost. WDM can accommodate more users, but it is more costly to multiply the capacity by using multiple wavelengths in one fiber without increasing the data rate [9-10]. WDM uses in access networks was invented in the late 1980s, where WDM-PON were developed to support future high bandwidth, residential and back-up services [9]. Since light signals are attenuated during optical fiber communication systems for long distance transmission , we need an optical amplifier to recover from this problem as done by EDFA [11]. When WDM networks use EDFA, a cost-effective solution (increasing network capacity demand for internet services) will be provided [8]. Different investigations have been done for WDM technology. Rajalakshmi *et al.*, [6] confirmed that WDM PONs performance is better than TDM PONs using 16 users. Gujral *et al.*, [7] concluded that the WDM System integrated with EDFA gives the optimized Q-Factor. Yousif *et al.*, [8] demonstrated by using array waveguide gratings AWGs in the system is to increase the capacity , security and privacy. AWGs are used in wavelength division multiplexing (WDM PON) for multiplexing and demultiplexing of different wavelengths. Sindhi *et al.* [11], demonstrated that the WDM system for 32 channels using EDFA has a good performance of BER and Q factor, where the optimum fiber length is about 5 m. Almalaq *et al.*, [12] demonstrated that the Q-factor, eye height, and threshold decreased when lengths of fibers increased with analysis of transmitting 40Gb/s coarse WDM. In this work we intend to analyze the WDM PONs performance using different fiber lengths, CW laser powers, data rates and number of users, by calculating BER and quality Q-factor.

The Passive Optical Network (PON) is an optical fibre-based communication network [13]. It is designed to give subscribers virtually unlimited bandwidth, a (PON) enables a service provider to deliver a true triple play offering of voice, video and data [14], a (PON) is a point-to-multipoint optical network, where a Central Office (CO) Optical Line Terminal (OLT) is located Linked to several Optical Network Units (ONUs) via one or more I: N optical splitters at remote nodes[15,16]),the OLT-ONU network is passive i.e., no power supply requirement[17],nowaday, Passive Optical Networks (PONs) are considered as a promising solution technology for the future high speed access networks and for Fiber To The X (FTTX)[14,18]),due to its high capacity, greater coverage range, upgradability and cost efficient system[19]). The architecture of the FTTx (fiber-to-the-building, fiber-to-the home, fiber-to-the-node, fiber-to-the-premises, fiber-to-the-multi dwelling-unit, etc) provides an enticing solution for fiber optic communication networks ,with FTTx a P2MP passive optical network (PON) allows multiple customers to share the same link without any active components [20,21,22]). Bringing the fiber directly to each subscriber, in some cases, may not be necessary. The splitter fibers, in that case, are transferred to ONTs, and short copper-based links (typically VDSL providing sufficient bandwidth for short-distance triple-play services) are used for the final connection: fiber to-the-building (FTTB)[23,24].

Predicting the performance of fiber optic communication systems through numerical simulations has began to be an increasingly important way to complement expensive system experiments, and explore large variations in system designs that are difficult to study experimentally [25]. Measuring an optical signal quality is the most important task in optical communication systems. Optical system quality evaluated by Q-factor BER is mainly depending on input power, bit rate, channel length, modulator, wavelength and receiver type [26 ,27,28]. Hence, the capacity demands for data transmission and optical fiber communication (OFC) technology have undergone an enormous growth. During long distance transmission in OFC systems, light signals get attenuated; and to recover from this problem we need an optical amplifier such as erbium doped fiber amplifiers (EDFA) [29].

The infrastructure of access networks have suffered from limited bandwidth and high network management cost, till the maturity of optoelectronics for telecom networks, [30], where PONs have emerged as the most promising solution for fiber-to-the-home (FTTH), fiber-to-the-business, and fiber-to-the-curb, and broken through the economic barrier of traditional point-to-point solutions [31]. PONs are considered as a successful access architecture that can provide high capacity and long reach by implementing optical fiber, since these offer services by various multiplexing schemes, like TDM, WDM and Hybrid WDM /TDM [32]. Although TDM PONs uses a single wavelength providing more channels, they moderate bandwidth with reasonable cost [33]. WDM can support more users, but it is more expensive when using multiple wavelengths in a single fiber to multiply the capacity without increasing data rates. Hybrid WDM/TDM networks have positive characteristics in both schemes, and can at the same time meet the PON characteristics [34-35]. FTTH, as a promising solution for networks, provides large transmission distance, high capacity, large bandwidth and multi-service convergence access network [36].

Different investigations have been conducted for TDM ,WDM and hybrid (WDM-TDM) PON. Jacob *et al.*, [37,38] have studied the performance of unidirectional WDM PONs with 2 users and reported high Q-factor and low BER, compared to that of 2 users TDM PON systems. Rajalakshmi *et al.*,[33] demonstrated that WDM PON network performance is better than TDM PON networks [39].Hybrid PON (WDM/TDM) performance analysis with unequal channel spacing performs better than equivalent channel spacing with investigated hybrid PON at bit rate 5 Gbps per wavelength For range 50 km without using any amplifier [40]. On another hand, Rakesh *et al.*,[41] analyzed the performance of hybrid (WDM/TDM) PON with 128 users at 1.25 Gbps up to 28km distance. Abdalla *et al.* [40], demonstrated that the hybrid architecture has great performance compared to the 10G TDM-PON. Hambali *et al.* [42] demonstrated that in Hybrid Coarse Wavelength Division Multiplexing/Time, Division Multiplexing (CWDM/TDM), the Q-Factor's value on passive splitter

32 users is capable of reaching a maximum value of 40 km at cable length, which is equal to 6.62. For 64 users the length up to 32,5Km with Q=6,28 and for 128 users the length up to 23,5Km with Q=6,85 with. Kumari *et al.* [43] concluded that TWDM-PON is suitable for low-cost, high-speed and true long-distance application with favorable input power. Mandal *et al.* concluded that WDM-RoFSO-PON could become a cost-effective Triple-play services (TPS) solution in the ubiquitous multi-service wireless network of the next generation for several application domains, e.g. two buildings, two ships; Institutes of education, terrestrial broadcasting and the first/last mile Dense urban areas, and rural areas and Proven for Free-Space Optics Next Generation Network. 10 Gb/s downstream link, 1.25 Gb/s upstream link data/voice signal, and 1.49 Gb / s video signal are transmitted successfully through FSO-Link 500 m [44]; Das demonstrated that the Return to zero (RZ) pulse carving is preferred in the WDM architecture, as it reduces the pulse duty cycle and extends the optical Total spectrum. It improves sensitivity to the receiver, polarization mode dispersion (PMD) tolerance And other high-data results [45]; Anindya Sundar Das *et al.* proposed a novel architecture of cost effective bidirectional wavelength division multiplexed passive optical network (WDM-PON) system based on reflective semiconductor optical amplifier (RSOA), using optical carrier suppression (OCS) method, for downlink and uplink transmission make it suitable for the long haul communication system [46].

Optical fiber is a dielectric wave guide or medium in which information (voice,data, or video) is transmitted in the form of light through glass or plastic fiber [47], it is composed of a transmitter, optical lines and a receiver[48] Since the mid-90s there was a passive optical network (PON) technology available. It is a network architecture that uses a point-to-multipoint or point-to-point systems that allows a single optical fiber to serve multiple premises to deliver fibre cabling and signals to the home.Passive Optical Network (PON) does not have any active components between Central Office(CO) and client. Passive equipment does not need electrical power, they direct traffic sgnals within different optical wavelengths Flows of voice video and data trafic (triple play) can be easily implemented using different wavelengths [49].

Currently, wavelength division multiplexing optical networks (WDM ONs) are commonly used in telecommunications infrastructures [50], wavelength Division Multiplexing (WDM) is a system in which single users want to operate at the appropriate electronic rate, using a large number of mismatches in optoelectronic bandwidth. After several WDM channels occur concurrently on a single cable,we can also use broad fiber bandwidth bandwidth. Both elements of A wdm mechanism need to operate at electronic speed, which makes the operation of each WDM mechanism much simpler than other conventional mechanisms [51].

The receiver's purpose is to transform the fiber optic signal to an electrical signal. The optical receiver requires a signal processing circuit, an amplifier and a photodetector. When a signal is received the first thing a receiver does is transform the optical signal into an electrical signal. The signal is then amplified to an optimal level, sothat the following step can be carried out[48].

Positive-intrinsic-negative (PIN) diodes and avalanche photodiodes (APDs) are mainly used as optical receivers.photodiodes are semiconductor devices that respond to particles and photons with high energy. This acts by collecting photons and generates a current motion in an external circuit[48], PIN diodes are structurally simple, and relatively inexpensive.

The main drawback of PIN diodes is their small gain. Their thermal noise may be more significant than the signal when operating at extremely low signal levels. Compared to the diodes with PIN, APD’s are more complicated and costly. As regards .sensitivity, they outperform PIN diodes, as their internal gain eliminates the effect of thermal noise[52,52,54]).

Different investigations have been conducted for comparisons between PIN and APD photodetectors. Md. Mashrur Islam1 et al (2019)[55] demonstrated that APD photodiode gives a better performance as a receiver in FSO transmission system as compared to PIN photodiode, O.Kharraz et al (2013)[56]they found that the benefit of the APD photodetector, which results in higher SNR, has made it more suitable for long haul communications, as a high-speed receiver in high bandwidth and bit rate applications,and it's a good candidate in highly sensitive applications for network access than PIN but APD is unavoidable that the high cost . Due to the high temperature nature and applied voltage, the APD is less stable than the PIN , Zahra Shahsavari et al(2015)[57] evaluated and compared between the PIN photodiode and APD photodiode, demonstrated that due to more sensitivity of APD diode, output parameters were better than PIN diode and APD is still the most practical detector,Manpreet Kaur et al(2018)[58] compared also between PIN and APD performances ,they demonstrated that APD performs better than the PIN photodiode. Singh *et al*(2012)[59] said that by using the APD photo detector, results have been improved. The values for Q Factor has been also improved. Millovancev *et al.*, (2019)[60] improved that APD receiver reaches an excellent sensitivity, Aldouri *et al(*2019)[61] illustrated that APD is high resolution effect more than that at using PIN as appeared in the values of BER. Transmitting optical signals over optical networks (ONs) is often accompanied by losses due to the dispersion and non-linearity effects (Fiber-Optic Communications, book chapter 2008)[62]. Erbium doped fiber amplifiers (EDFA) are the widely amplifiers that PONs have used and optical telecoms have benefited from to predict and improve system performance(Liang B. Du et al ,2019[63]; J. Gujral et al,2013[64]).

Hybrid WDM/TDM multiplexing is expected to be a strategy for PON-based access networks of the next generation [65,66].TDM-PONs are inexpensive, these cannot operate with potential network evolution needs regarding the aggregated bandwidth [67]. Nowadays, TDM is not usually exploited since it restricts users' number and bandwidth [68]. This issue can be addressed by using WDM PONs, where optical network units (ONUs) are allocated for individual data wavelengths so as a fiber bandwidth is used to package data, voice and video services [67], and WDM offers several wavelengthsfor each consumer [68]. WDM-PON networks are capable of delivering services over long distances to a wide number of users [69]. Besides, Hybrid WDM/TDM-PON architectures provide customers with a cost-effective, long range and broad bandwidth [67,70]. On the other hand, photodetectors as main components of optical networks, are receiving blocks designed to transform optical signals containing information into transmission line electrical signals.

Different investigations have been conducted for TDM, WDM and hybrid (WDM-TDM) PONs. Hambali *et al.* [71] reported that for a CWDM/TDM-PON hybrid network (with NG-PON2 technology, 40/10 Gbps bit rates and 10/20 km cable lengths), Q values of 6.62 and 6.288 for (40 km, 32 ONU) and (32.5 km, 64 ONU), respectively. Moustafa *et al*. [66] proved that extending WDM/TDM-PON to 80 Gbps over a 50 km transmission distance with a fair 10 dBm of benefit, reporting a combined BER of 10^{-13} with a reasonable 10 dBm launched power. Mandal *et al*. [67] simulated an optimized hybrid WDM/TDM-PON-based FTTH access network to provide triple play services for 128 users, reporting a Q value of 6.5 and a minimum BER of $6.39.10^{-9}$ over a 50 km transmission distance with a bit rate of 10 Gbps. Z. Via studying the performance of APD and PIN photodetectors in hybrid TDM/WDM-PONs,

IV.2. Performance Analysis and Improvement Of (2-10) Gbps WDM PON using EDFA amplifiers

Here, we investigate a data transmission of 2 to 10 Gbps WDM PONs with 32 ONUs and single EDFA amplifiers, using Optisystem software, and design such transmitters in terms of fiber length, power of continuous wave (cw) laser, data rate and users' numbers. We also focus on achieving appropriate Q-factors and bit error rates, by analyzing the performances on the basis of transmission distance from 5 to 100 km in terms of Q-factor, minimum BER and output power. When dispersions are lowest and ONUs number is highest, EDFA-EDFA provides better Q-factors, and lower BERs and output powers[72].

IV.2.1 Simulation Tools (OptiSystem Software)

As innovative optical communication system simulation software, OptiSystem has been studied by Optiwave to meet academic needs of system designers, optical communication engineers and researchers [www/opti]. The components library of OptiSystem includes plenty of components enabling to enter parameters measured from real devices, and integrates with test and measurement equipment from different vendors. Using OptiSystem, we can incorporate components based on subsystems, or utilize co-simulation with SPICE/MATLAB. To predict the system performance, OptiSystem calculates BER and Q-Factor using semi-analytical techniques or numerical analysis for systems limited by inter-symbol interference and noise .see (Fig IV.1)

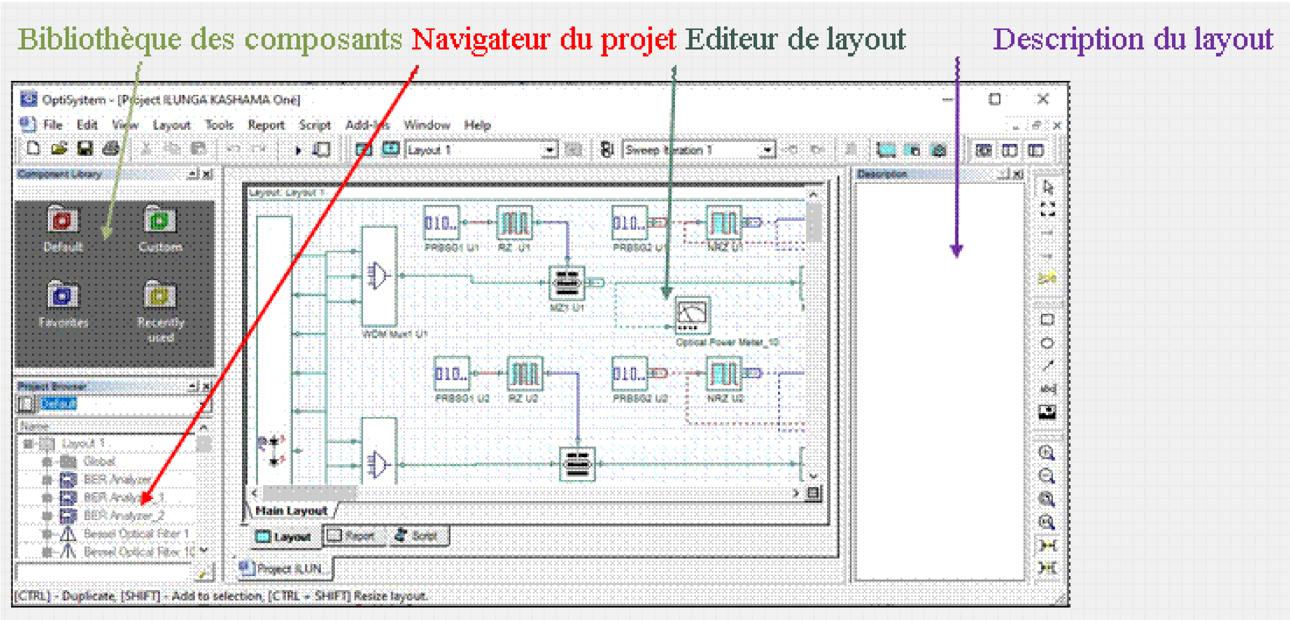


Figure IV .1 Graphical interface of the OptiSystem software

OptiSystem is a self-contained solution that does not rely on any other simulation frameworks. It is a system-level simulator that is based on realistic simulation of fiber-optic communication systems. It has a strong new simulation environment as well as a hierarchical component and system description. Its features can be be expanded by adding user components, and it can be easily interfaced with a broad range of tools[73].

The OptiSystem graphical interface contains the following main windows:

- Components Library: The Component Library gives us access to the different components to design and create the desired system.
- Project Browser (Current Project): This window contains all the components used in the project in order to be able to access the different components more quickly, especially in the case of a complex project that contains a large number of components;
- Layout Editor: This is the main window in which you insert components into the layout, edit components and create connections between components. It allows editing and configuration of the layout being designed;
- Layout Description: Visualizes and displays the various files and components corresponding to the current project.

Benefits

- Rapid and low-cost prototyping and Global understanding of system performance.
- Simple access to large quantities of system characterization data.
- Scan and optimize parameters automatically.
- The assessment of parameter sensitivities aids in the determination of design tolerances.
- Prospective clients will be shown a visual representation of design alternatives and situations.

Applications : OptiSystem's wide range of applications include:

- Optical communication system design from component to system level at the physical layer.
- TDM/WDM network architecture, transmitter, channel, amplifier and receiver design.
- Passive optical networks (PON) based FTTx and Free space optic (FSO) systems.
- Radio over fiber (ROF) systems and SONET/SDH ring design.
- Estimation of BER and system penalties with different receiver models.

a) Bit rate Error (BER)

In telecommunications transmission is the percentage of bits that have errors in relation to the total number of bits obtained in a transmission, usually expressed as 10 to a negative amount. For example, a transmission could have a 10^{-6} BER, which means that one bit was in error out of the 1,000,000 bits transmitted [9].It is an indication of how data has to be retransmitted because of an error a communication channel that has been altered due to noise, interference, and distortion or bit synchronization errors [67].BER should be maintained at a level less than 10^{-9} for acceptable performance of the system [67].

b) Quality factor (Q-factor)

Q-factor indicates the energy loss relative to the amount of energy stored within the system (Q>6), i.e, the higher the Q the lower the rate of energy loss, and then the oscillations will reduce more slowly [67].Q-factor is defined as:

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0} \tag{IV.1}$$

where $|\mu_1 - \mu_0|$ denotes the separation between the intensity levels of "1" and "0", and $\sigma_1+\sigma_0$ is the sum of the standard deviations of the intensities around the "1" and "0"levels. Based on the Gaussian approximation for the noise distribution in the received signal. Since BER is not counted directly but measured by the evaluation of statistical fluctuations, these are characterized by Q-factor given as:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) = \frac{1}{\sqrt{2\pi}} \frac{1}{Q} e^{-\frac{Q^2}{2}} \quad \text{(IV.2)}$$

Fig IV.2 depicts the relationship between BER and Q Factor, demonstrating how as the bit error rate increases the quality of signal decreases[67].

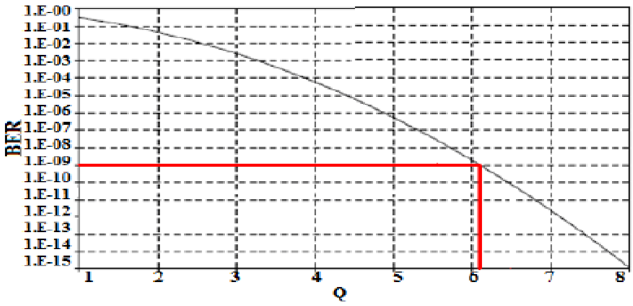


Figure IV.2 Relationship between BER versus Q Factor [67]

A greater number (Q-factor) means that the pulse is relatively noise-free [67]

$$Q(dB) = 20Log\sqrt{SNR}.\sqrt{\frac{B_0}{B_C}} \quad \text{(IV.3)}$$

B_0 is the optical bandwidth of the photodetector; B_c is the electrical bandwidth of the receiver filter. Thus,

$$Q(dB) = SNR + 10Log\frac{B_0}{B_C} \quad \text{(IV.4)}$$

From equation (IV.4), Q is proportional to Signal-To-Noise Ratio(SNR).

c) Eye diagrams

A great deal of system performance information can be deduced from the eye pattern display. To interpret the eye pattern, consider Fig.IV,3 and the simplified drawing shown in Fig.IV4. The following information regarding the signal amplitude distortion, timing jitter, and system rise time can be derived:

- The width of the eye opening defines the time interval over which the received signal can be sampled without error due to interference from adjacent pulses (known as intersymbol interference).
- The best time to sample the received waveform is when the height of the eye opening is largest. This height is reduced as a result of amplitude distortion in the data signal. The vertical distance between the top of the eye opening and the maximum signal level gives the degree of distortion. The more the eye closes, the more difficult it is to distinguish between 1s and 0s in the signal[67].

The height of the eye opening at the specified sampling time shows the noise margin or immunity to noise. Noise margin is the percentage ratio of the peak signal voltage V1 for an alternating bit sequence (defined by the height of the eye opening) to the maximum signal voltage V2 as measured from the threshold level, as shown in Fig. IV,3 That is

$$Noise\text{ margin (present)}=\frac{V_1}{V_2}\times 100\,percent \quad \text{(IV.5)}$$

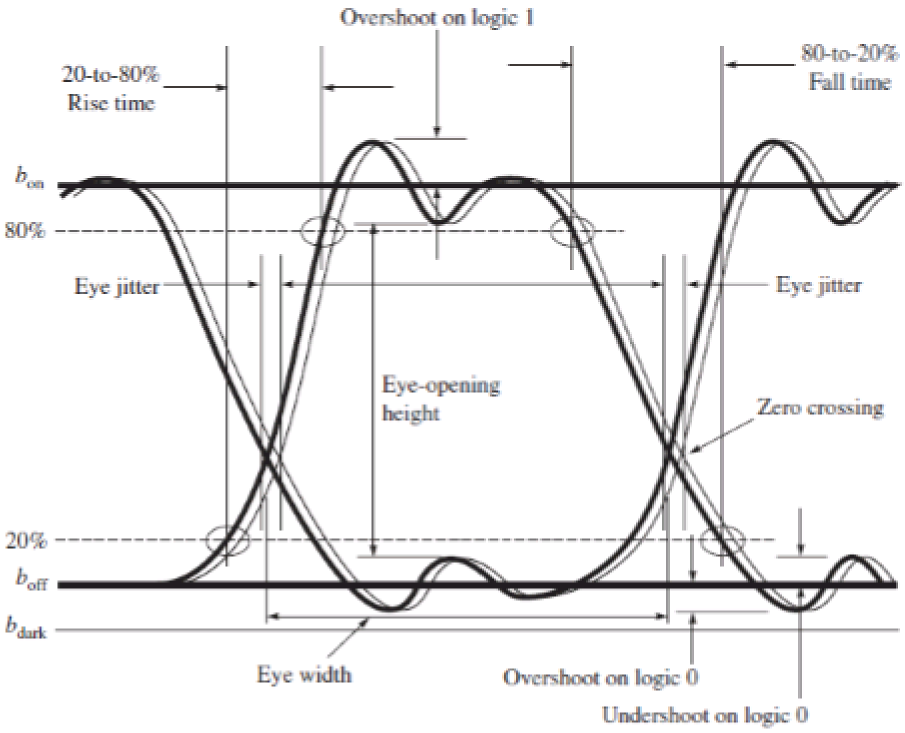
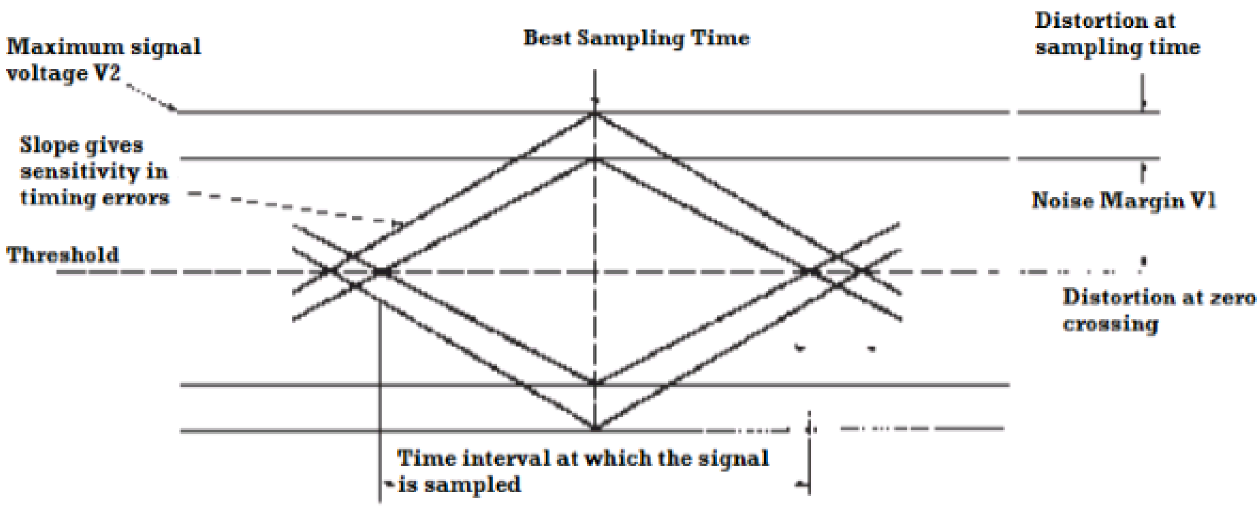


Figure IV. 3 General configuration of an eye diagram showing definitions of fundamental measurement parameters[67].



FigureIV.4 Simlified eye diagram showing key performance parameters [67]

- The sensitivity of the system to timing mistakes is determined by the rate at which the eye shuts as the sampling time is altered (i.e., the slope of the eye-pattern sides). As the slope grows more horizontal, the likelihood of timing mistakes rises.
- Noise in the receiver and pulse distortion in the optical fiber cause timing jitter (also known as eye jitter or phase distortion) in an optical fiber system. If the signal is sampled in the middle of

the time period (i.e., halfway between when the signal reaches the threshold level), the amount of distortion T at the threshold level reflects the degree of jitter. Thus, timing jitter is given by

$$Timing\ \text{jitter (percent)} = \frac{\Delta t}{T_b} \times 100\ percent \qquad (IV,6)$$

- Traditionally, the rise time is defined as the time period between when the signal's rising edge reaches 10% of its final amplitude and when it reaches 90% of its final amplitude. When monitoring optical signals, however, these spots are frequently hidden by noise and jitter effects. As a result, the more distinct values at the 20% and 80% threshold points are often assessed. The approximate connection may be used to convert a 20 to 80 percent rise time to a 10 to 90 percent rise time[67].

$$T_{10-90} = 1,25T_{20-80} \qquad (IV.7)$$

IV.2.2. WDM PON System

As a potential technology, WDM PONs that use multiple wavelengths in single fibers to multiply the capacity without increasing data rates, have been widely researched. PON architecture consist of a Single Mode fiber which connects a Central Office to the network distribution unit which consist of multiplexers and demultiplexers [49], as shown in (Fig IV.5)

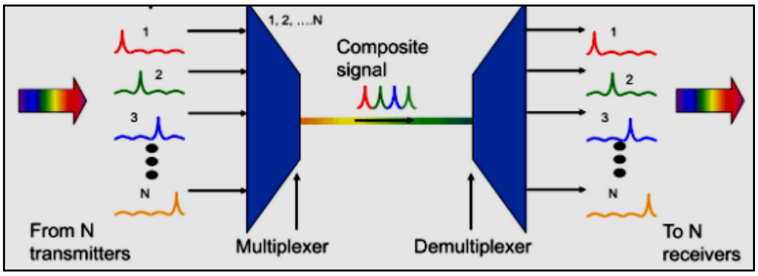


Figure IV.5 WDM PON network [4]

IV.2.2.1. WDM Technology:

WDM PONs, among the most widely used technology for high-capacity optical communication systems, vehicle optical-based communications that introduce good data transmission rates and large bandwidths [49,74]. communication channels are allocated to different wavelengths that are multiplexed on to a single fiber. These wavelengths are then demultiplexed at destination and spatially separated to different receiver channels [49,74].

IV.2.2.2. EDFA amplifiers:

EDFA, owning large gain bandwidth, amplifies data channels next to highest data rates lacking presence of gain shrink, and make use of optical amplifiers due to low loss optical window of silica fiber. Usually two wavelength windows C and L-Band (1530-1560) and (1560-1600) nm are respectively used. An expansive wave length range(1500-1600) nm can be amplified by EDFA simultaneously.Due to this property, EDFA became every useful in WDM for amplification[10,11].

- The gain that EDFA provide, as a function of length, is the ratio of the signal power at the fiber output to that introduced at the fiber input, given as [11]:

$$G = P_s(L)/P_s(0) \qquad \text{(IV.8)}$$

Where, G is the signal power at the length L, and $P_s(0)$ is that at the input of the EDFA.

- The signal to noise ratio (SNR) at the amplifier output is decreased by adding the ASE noise produced across the amplification process. An SNR ratio reduction from input to output of the amplifier is illustrated as noise figure (NF), which is utilized for electronic amplifiers.

$$NF = (SNR_{IN})/(SNR_{OUT}) \qquad \text{(IV.9)}$$

To determinate signal spectra, power levels, eye diagrams and its related parameters, several tools Optisystem could software offer us, such as eye opening , BER and Q-factor. (Fig IV.6) below, shown the schematic design of EDFA involved in the WDM system. It consists of 8 input channels WDM transmitter, a multiplexer, a fiber length of 5m, an EDFA amplifier, a demultiplexer, a PIN photodetector, a low pass Bessel filter and a 3R regenerator.

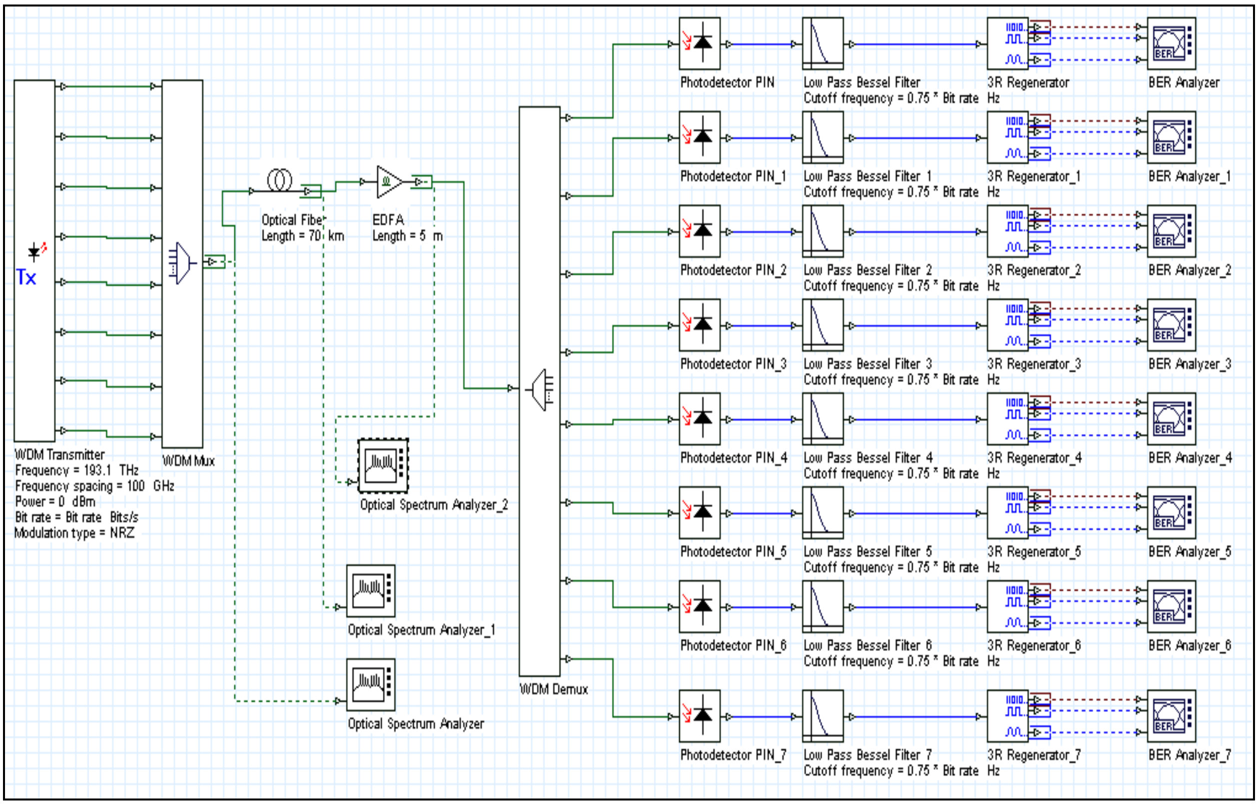


Figure IV .6 WDM PON simulation setup

To study the Q-factor and BER of WDM PON, input-data related to WDM-transmitter are chosen such as: Input power 6 dBm, frequency 193.1THz, modulation Type:NRZ and Frequency spacing : 100GHz.

IV.2.3. WDM PON with and without EDFA (For 8 users)

Using optisystem, our WDM PON model for integrated with and without EDFA was simulated, so as the bit rate and the EDFA length were respectively 8 Gbps and 5 m. The CW laser power and frequency were0 dBm and193,1THz,with 100 GHz (0.8nm)channels spacing and a length of 60Km.

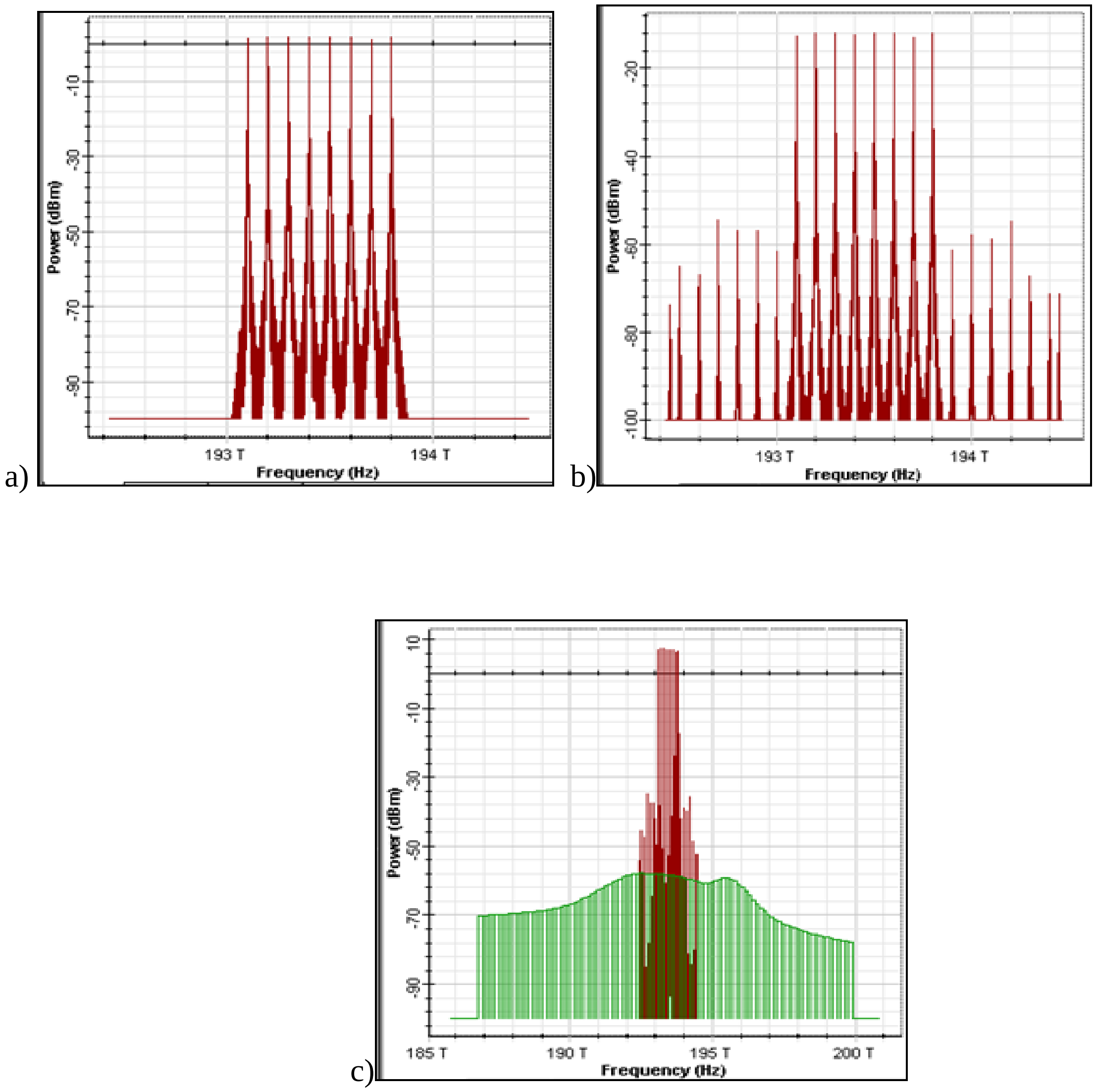
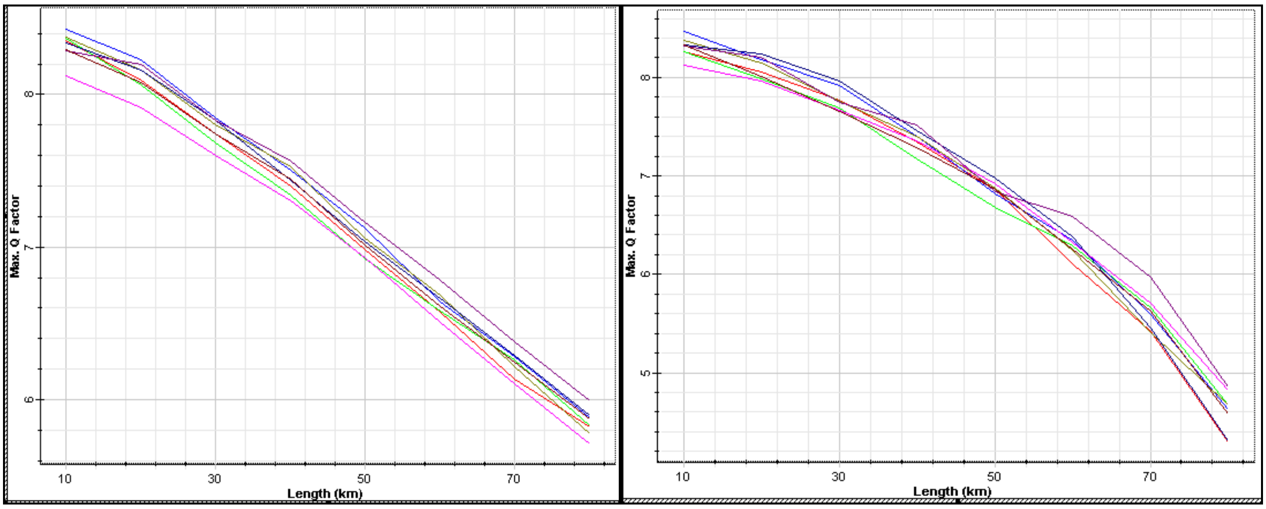


Figure IV.7 Optical Spectrum Analyzer *a*) 8 x 1 Multiplexer Output Power *b*) Optical fiber Output *c*) EDFA Output.

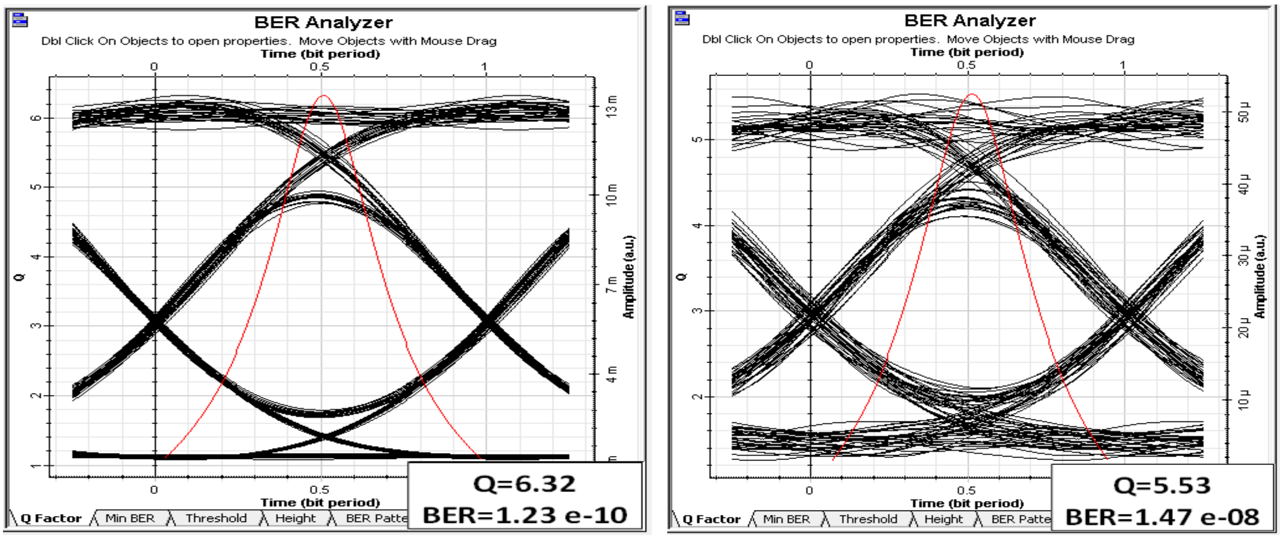
Viewed results from *a*) 8-channels multiplexer are shown in (Fig IV.7) ,b) optical fiber , where the output powers of different wavelengths from 193.1 to 193.8 THz, were 0 dBm and –10 dBm, respectively. *c*) EDFA output of 8-channels shows inversely in terms of noise figure a 5 dBm maximum. The green wave represents the noise, while the red symbol illustrates the wavelength sample. After analyzing, it can be concluded that EDFA is used to compensate the optical signal loss to increase the transmission length. The analyzed 8-channels Q-factor by varying fiber length between 5 and 80Km is shown in (Fig IV. 8)



a) b)

Figure IV.8 Max Q-factor vs Length for 8channel (*a*) WDM PON using EDFA, (*b*) WDM PON without EDFA.

From these results, one can conclude that WDM-PONs integrated with EDFA give optimized Q-Factor and BER for WDM PON long distance: Q-factor was 6.32 for WDM PON integrated with EDFA while it was 5.53 without EDFA for length 66 Km. As for the eye diagram (Fig.IV. 9 *.a)*, a big opening is given, meaning that inter symbol interference (ISI) is low.



a) b)

Figure IV.9BER analysis showing Eye diagrams of downlink (Q-factor in red curve), for a length of 66Km: WDM PON (*a*) using EDFA, (*b*) without EDFA.

IV.2.4. WDM PON by using EDFA (for 32 users)

IV.2.4.1 . Impact of CW Laser Power

The first scenario illustrates a maximum power of CW lasers when the D of the PON, D=8Gbps,and the fiber length is 70km. The performances, in terms of Q-factor and BER with different values of P are shown in (Fig IV.10),where the transmitted power varies between –6 and 10 dBm.

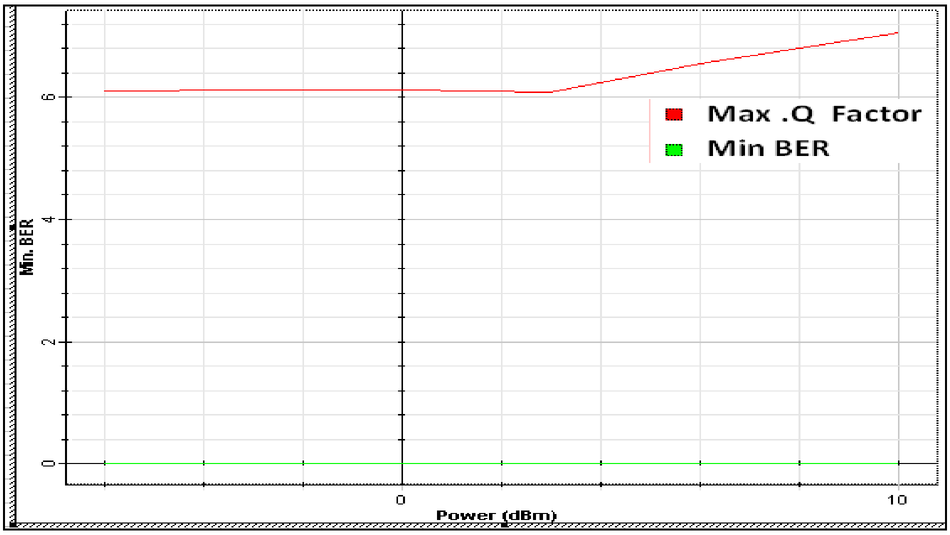
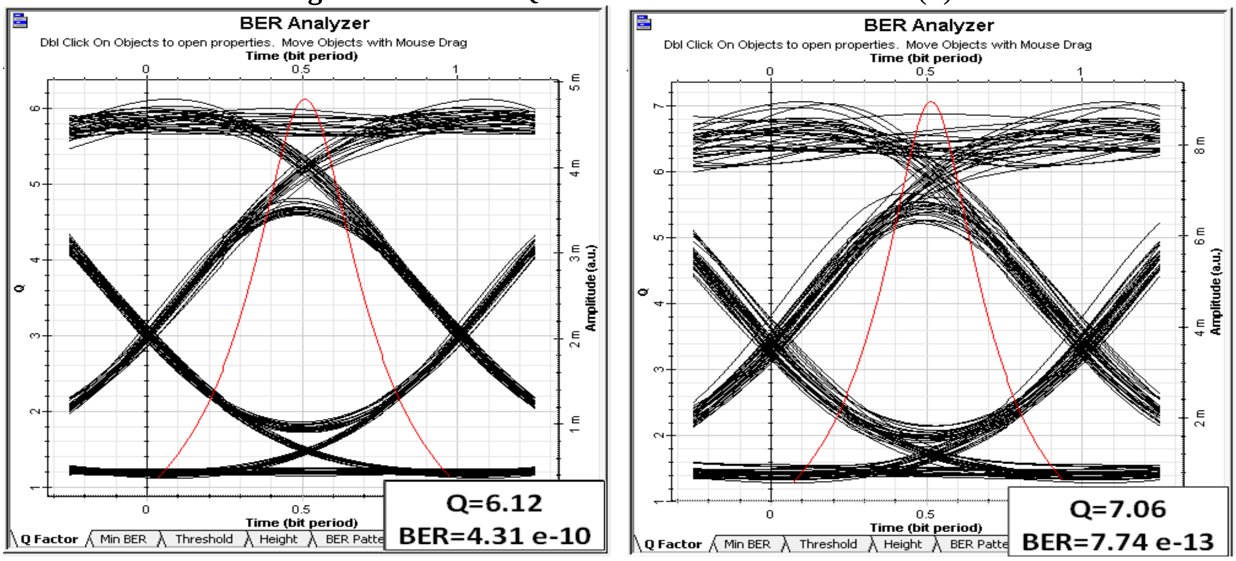


Figure IV.10 Max Q-factor and Min.BER vs. Power (P)



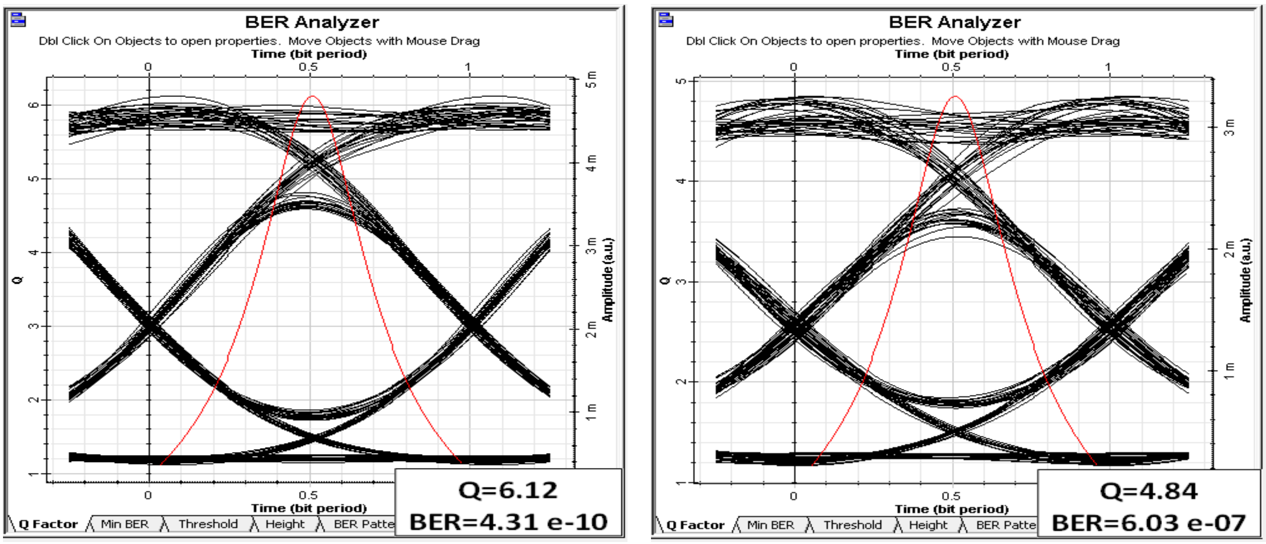
a) *b)*

Figure IV.11 BER analysis showing Eye diagrams of downlink, for : *a*) P = 0 dBm, *b*) 10 dBm.

From (Fig IV.10), it is worth to notice an increase of Q-factor when powers (P) increase from –6 to 10 dBm, and that BER decrease, explained by the fact that P should be greater than 0dBm in order to ensure a BER well below 10^{-9} and a Q beyond 6, that optical networks require. (Fig IV.11) shows results of downlink, as eye diagrams for P values of 0 and 10 dBm (*a* and *b* respectively).

IV.2.4.2. Impact of transmission distance

The second scenario investigates the fiber length maximum when the CW laser power number of users and D are fixed respectively at 0 dBm, 32 and 8Gbps. The fiber length transmitter-to-receiver varies between 5 and 100Km. (Fig IV.12 (*a*, *b*)) shows an eye diagrams change with the fiber lengths 70km and 100km, respectively. BER analysis and Q-factor results are shown in (Fig IV.13) below.



a) *b)*

Figure IV.12 BER analysis showing Eye diagrams of downlink showing Q-factor (in red curve) for L: *a*) 70 Km; and *b*) 100Km.

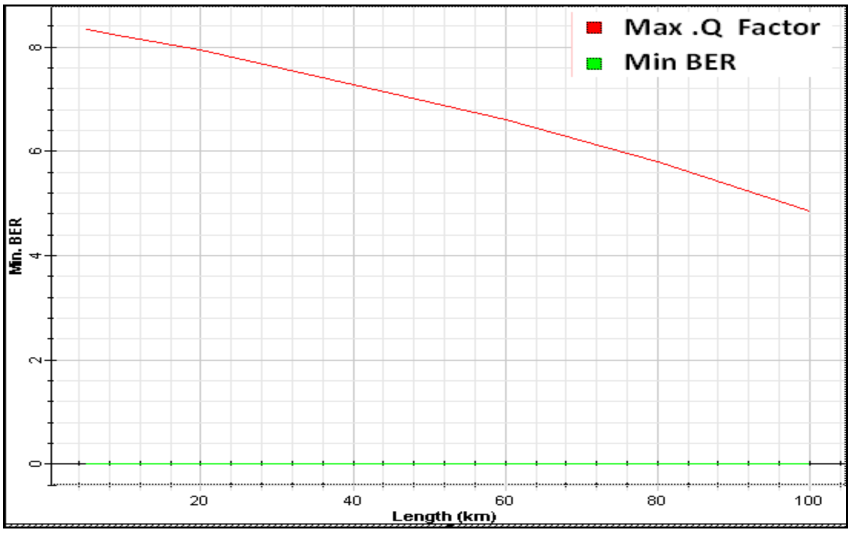


Figure IV.13 BER analysis and Q-factor results *vs* length Length.

One can notice that BER increases with distance increasing, in contrary to Q-factor that decreases while L increases, due to the loss of fiber. Hence, a fiber length of 70Km is suitable to be chosen as an optimum length, because at 70Km the system gave a Q-factor value of 6.23 and a BER about 2.122 $\exp^{-10}$ to satisfy the requirements of BER $<10^{-9}$ and Q>6.

IV.2.4.3. Impact of data rate

To evaluate the impact of data rate transmitter-to-receiver, this is varied between 2Gbps to 10Gbps. The performances in terms of both Q-factors and BER simulated with power CW laser at 0dBm for a link length of 70km and users' number of 32 is shown in (Fig IV.14).

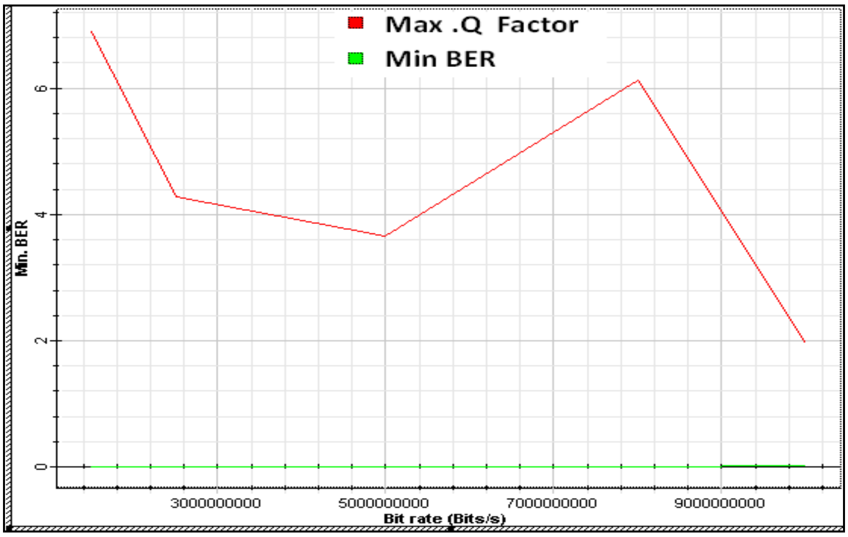
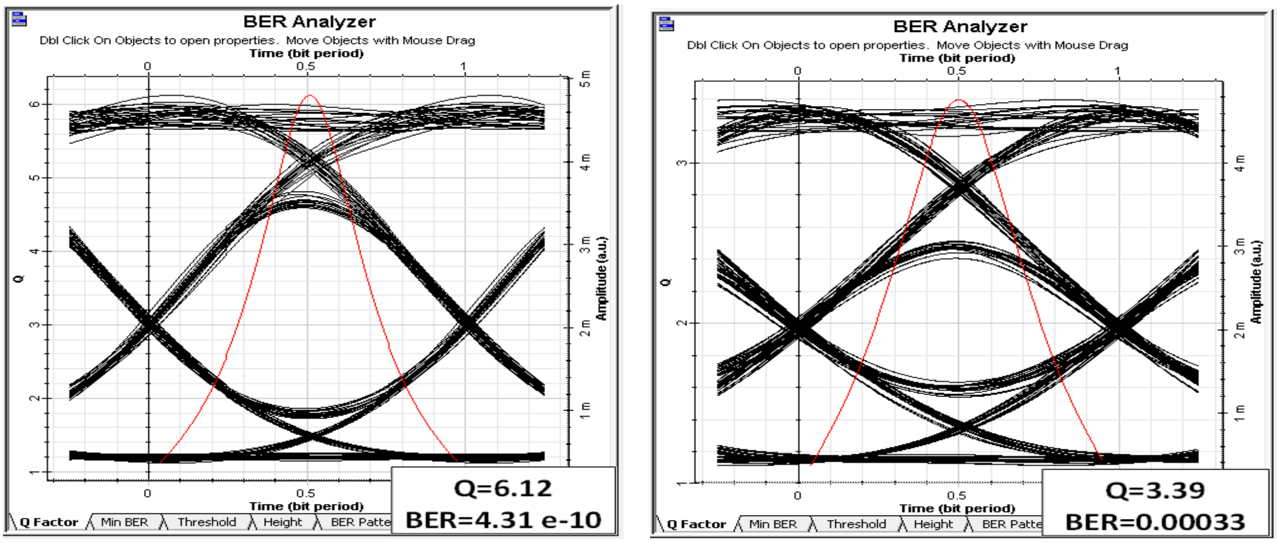


Figure IV.14 Max Q-factor and BER *vs* Bit rate.

The BER and Q factor are shown in (Fig IV.14), where one can notice that BER increases and Q-factor decreases (i.e. performance degrades) when the bit rate increases. Such performance degradation is explained by the increase of the interferences between the data bits in the channel. This leads to poorly detect the bits of receiver. Such result can be concluded as high data rate will give a lower Max Q-factor.(Fig IV.15 (*a* and *b*)) show eye diagrams when the data rate (D) is respectively taken to be 8 and 10 Gbps.



a) b)

Figure IV.15 BER analysis and Q-factor results (shown in red curve) for: (*a*) D = 8Gbps, (*b*) D =10 Gbps

IV.2.4.4. Impact of number of users

We considered the data rate of the WDM PON system, with D of 8Gbps, a distance of 70Km, and a power of 6dBm, by changing the parameters such as the users' number in the receiver side of the network, to we get more results. One can mention that the system performances (as shown in Fig

IV.16) were more deteriorated due to the fact that the increase the interference between the data bits, which leads to bad data detection. As a result, when the number of active users increases, the interference increases, and the performances of the system deteriorate more.

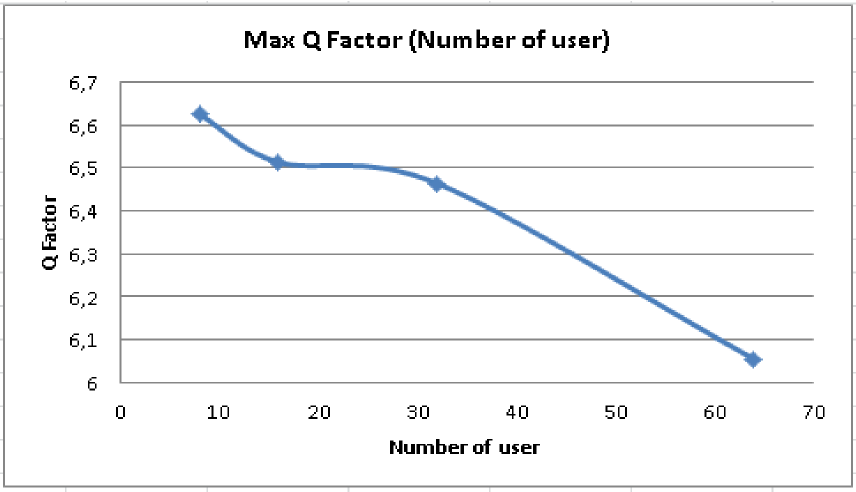


Figure IV.16 Q -factor *vs* Number of users.

IV.3. Performance analysis of TDM PON system for128 users using RZ and NRZ modulations

In this part we compare the most important modulation formats used in optical communications in terms of bit error rate and Q-factor. The main aim of these simulations is to assess their weaknesses, advantages and explore the functionality of these formats to meet potential network needs and tackle the growth of data traffic.Two basic format s in optical communication systems exist: non-return-to-zero (NRZ) and return-to-zero (RZ) [75]. Here, a device consisting of downstream optical fibre connectivity processing was used, and the system performance has been investigated using NRZ and RZ formats operating by varying bit rates , the length of the fiber, power of continuous wave (CW) laser and number of users. The analysis showed how exceptional the RZ modulation format compared with the conventional NRZ modulation design due to preferable inviolabilit to average peak power and non - linearity fiber. The results were assessed by the value of the quality (Q) factor, the bit error rate (BER) and the average eye opening using Optisystem7.0.

To unlock the ability of optical transmission systems and attain greater transmission efficiency, a lot of research for the non return-to-zero (NRZ) and return-to-zero (RZ) has been done in recent years,Whether NRZ or RZ is an important question to investigate the most optimal modulation scheme to achieve broad transmission spans .

Different investigations have been conducted for RZ and NRZ modulation, (Mustafa H. Ali *et al.*,2019)[18] demonstrated that the modulation format for RZ is superb compared with traditional NRZ modulation as it displays the best immunity to fiber non-linearities with any wavelength (1557-1490 nm) and also NRZ doesn't feel laser-phase noise, (Garima Arora *et al.*,2017)[21] demonstrated that the NRZ format is less affected by dispersion as compared to RZ format, (Robi Darwis *et al* .,2019)[76]concluded that NRZ is better than RZ when viewed in terms of BER(NRZ produces a small Bit Error Rate than RZ),(Ahmed Nabih Zaki ashed.,2019)[77] concluded that the Power obtained signal to noise ratio and average signal obtained usage of NRZ modulation to improve quality factor Modulation technique rather than RZ technique.(Amandeep Kaur *et al*.,2014)[78] demonstrated that RZ modulation format is superior to traditional NRZ format for this XG-PON device as it provides better immunity to non- linearities of fiber and NRZ has a superior tolerance for dispersion due to its larger spectrum performance than RZ . (Rakesh Goyal *et al*.,2012)[79]The comparative analysis and suitability for internet and voice over IP transmission of various data formats is being studied. It was observed that the data format most suitable for data transmission is NRZ. (Hazra *et al*., 2013) [80]demonstrated that NRZ Has high inter-symbol-interference sensitivity (ISI), but the downside of NRZ is that the transport in the midst of two protocols, the ability of transport waste, does not return to zero , (Jaswinder *et al*. Singh2011)[81]. demonstrated that RZ performs better than NRZ format for fiber optic CDMA.in comparison to NRZ and RZ modulations, RZ gives excellent performance at 2.5 Gb/sec than NRZ. (Rajdi AGALLIU, 2015)[72] show that the best system performance is achieved by RZ-DQPSK at both 10 Gbps and 40 Gbps transmission rates. (V. Senthamizhselvan *et al*, 2014)[73] show that the bit error rate is greatly reduced by using RZ modulation, (Gaurav Soni,2017)[74]NRZ is preferred as it has better tolerance toward timing jitters .

In this work, two optical systems were simulated:the first with (NRZ) and the second with RZ transmitter. We studied the performance of RZ and NRZ modulation in PONs (FTTH) , The performance of simulated system is investigated by varying input power , length of fiber ,bit rate and number of users. The results for downstream data formats NRZ and RZ were compared in terms of (Q) quality factor and bit error rate (BER) and eye opening using Optisystem 7.0.
Fig IV. 14 shows the system configuration of the optical network to study the performance of different modulation formats RZ and NRZ. For unidirectional PON with128 users by using an Erbium doped-fiber amplifier (EDFA) ,transmitting optical signals over optical networks (ONs) is often accompanied by losses due to the dispersion and non- linearity effects. EDFA are the widely amplifiers that PONs have used and optical telecoms have benefited from to predict and improve system performance [6], where a power splitter is used to receive and separate the users' signals. OLT plays the role of a transmitter block. As for the receiver block, it consists of ONT, a 3R regenerator and a BER analyzer. The system has been simulated using the wavelength 193,1THz for different fiber lengths. Data signal are generated at a data rate of 10 Gbps and CW laser power of 6dBm using Optisystem 7.0 , that Optiwave adopt as an innovative software to simulate optical communication systems to meet the academic needs of system designers ,optical communication engineers and researchers (www.optiwave.com)[85]

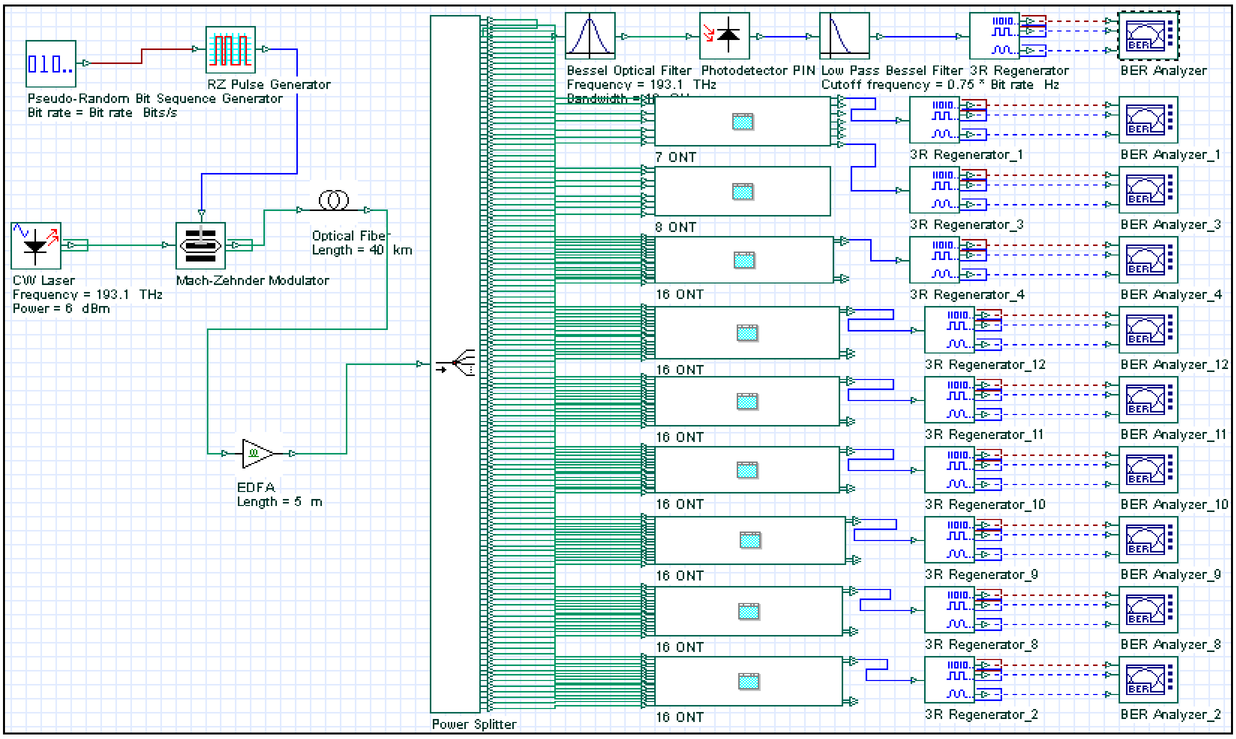


Figure IV.17 PON simulation setup

The results are evaluating quality factor (Q-factor) values, and rates of bit error (BER), as follows:

IV.3.1. Factor impacting the performances of systms

Our model has analyzed the Q-factor and BER of PON system, using RZ and NRZ modulations with 128 users.

IV.3.1.1. Impact of laser power

To estimate the impact of power CW laser, simulated Q-factors and BER are shown for different transmitted powers (P) ranging from -6 to 30dBm, with a data rate set at 10 Gbps for a connection length of 40 km and 60Km. For a number of users 128 who communicate simultaneously, the results show an increase in signal quality and a decrease in BER when P increases, as shown (Fig IV.18) and (Fig IV.19)

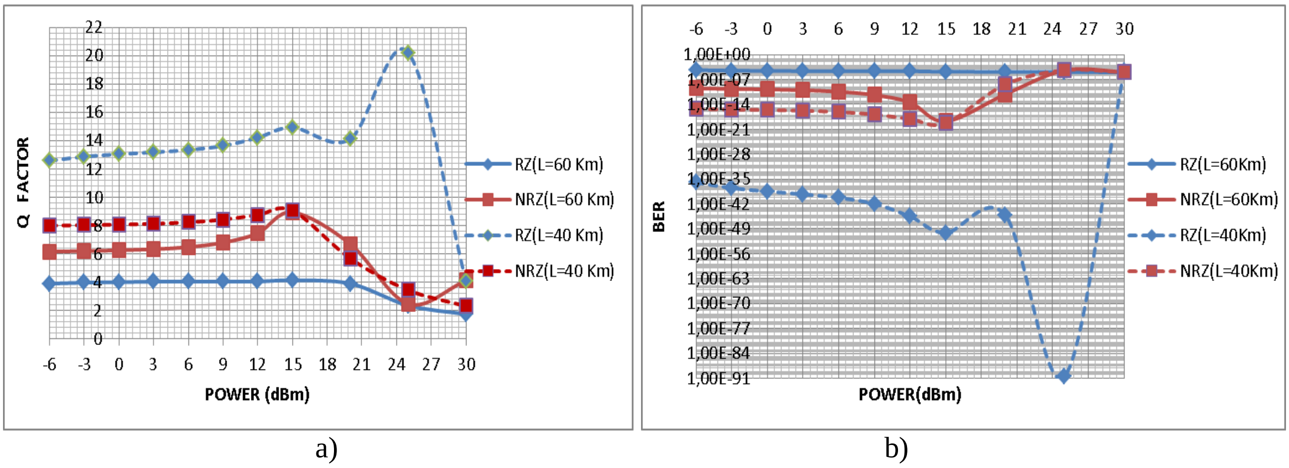
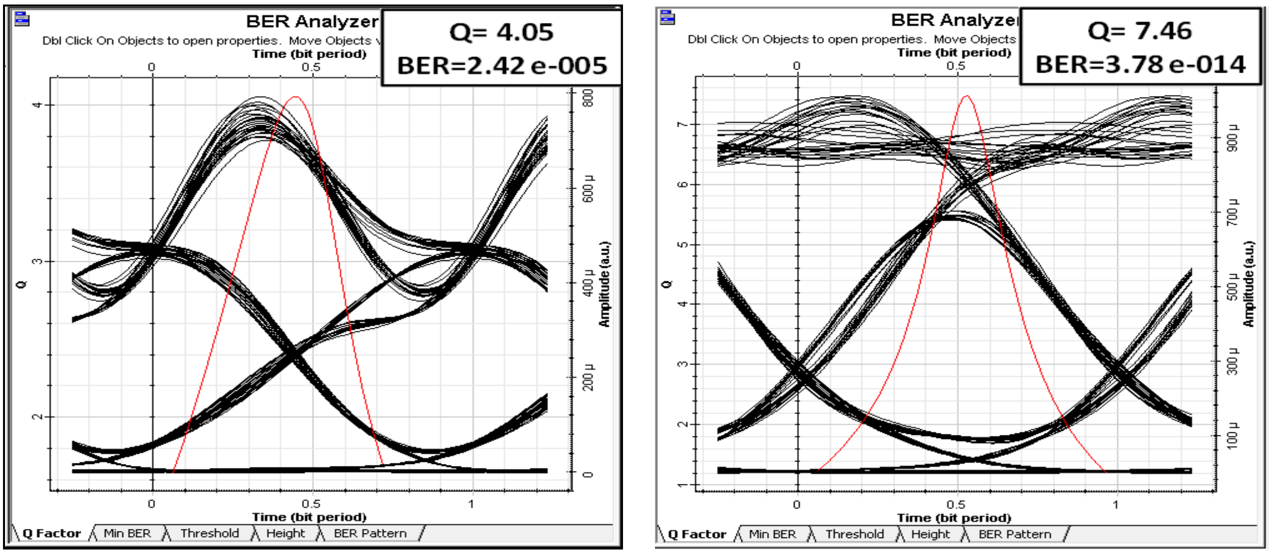


Figure IV.18 a) Q-factor and b) Log BER vs Power (P) using RZ and NRZ modulations

From (Fig IV. 18), we can see that when the power increases from -6 dBm to 30dBm, which means the receiver gets more power, the Q values increase and the BER decreases. Remember that P should be more prominent than 3dBm (for L=40Km) to ensure BER less than 10^{-9} and Q-factor greater than 6 (optical network requirements). And we show that we can clearly mention that the BER and Q-factor performance of the modulation RZ is suitable for the system performance for length up to 40Km. For L farther than 40Km (for ex, 60Km) the modulation NRZ is convenient for the system. For the eye diagram results, when the data bit rate is 10 Gbps, P is about 12dBm and L equals to 60Km with RZ and NRZ (see Fig V. 16 (*a* and *b*)).(for P=12dBm and L=40Km , using RZ Q=14,21 and BER=3,50 e -046, and using NRZ Q=8,75 and BER=8,51e-019).We can see that the RZ is not convenient for the system at 10 Gbps in long distances(ex 60Km) but NRZ is the best for the system .and in the same bit rate (10Gbps)for the short distance (40Km) RZ is convenient for the system especially for 20dBm(Q=16,42 for RZ and Q Peak up to 6,69 for NRZ).

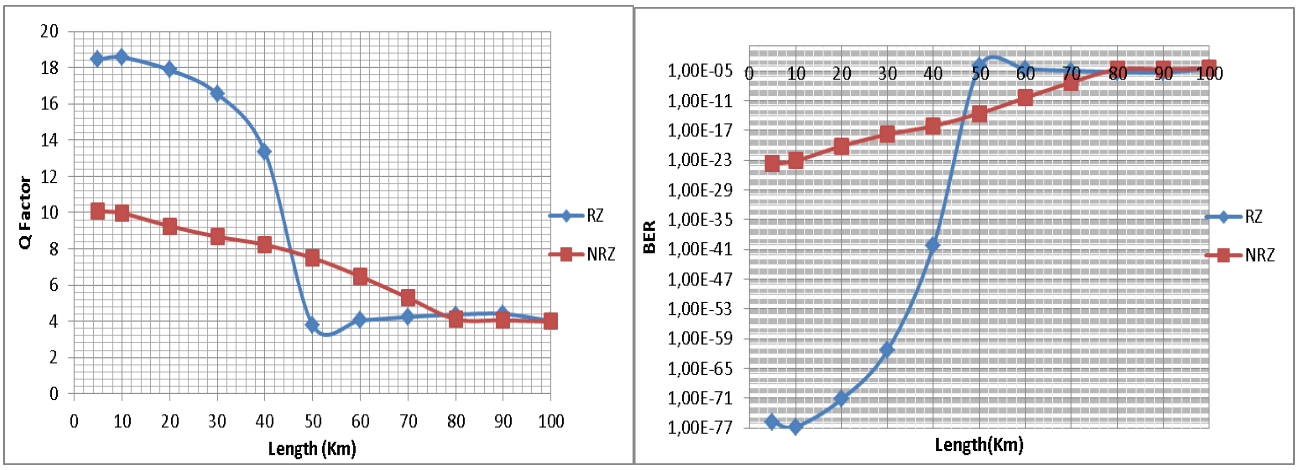


a) b)

Figure IV.19 BER analyzer shownning Eye diagram of downlink (Q-factor in red line), *a*) RZ, *b*) NRZ.

IV.3.1.2 Impact of transmission distance

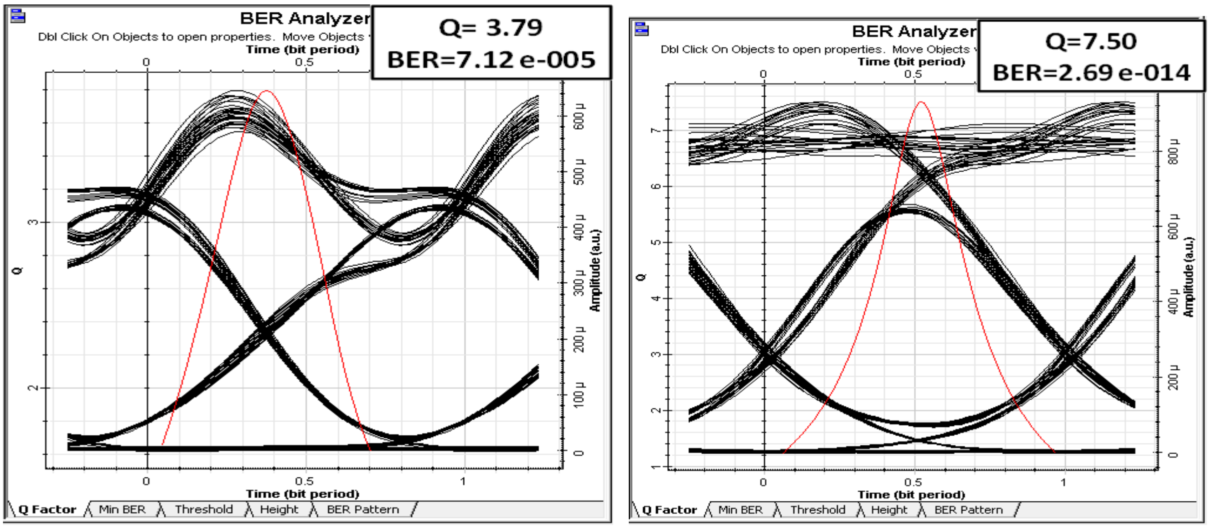
We assume that P=6dBm, D=10Gbps and users' number of 128, using RZ and NRZ. (Fig IV.18 (*a* and *b*)) show how eye diagrams of downlink, with a transmission distance (i.e. L) varying between 5 and 100Km). The results of Q-factor and BER are shown in (Fig IV.17 *)*.



a) b)

Figure IV.20 a) Q-factor and b) Log BER *vs* (L) using RZ and NRZ modulations

For link-lengths of 5 km to100 km respectively, the system BER and Q-factor performance versus link-length is shown in (Fig IV.20). It is worth noting that the greater the transmitter / receiver length, the more the Q-factor of the reception slowly decreases and BER decreases due to the loss of fiber (to satisfy the requirements of BER <10^{-9} and Q>6). Using modulation RZ is better for the system performance for length up to 45Km. for lengths beyond 45Km the modulation NRZ is more convenient for the system This indicates that NRZ is performing better than format RZ for the long distance as shown (Fig IV.22 (*a* and b))for L=50Km .(for L=30Km, using RZ Q=16,56 and BER=5,02 e -62, and using NRZ Q=8,67 and BER=1,56e-018)



a) b)

Figure IV.21. BER analyzer showing Eye diagram of downlink (Q-factor in red line) *a*) RZ, *b*) NRZ

IV.3.1.3. Impact of data rate

To assess the impact of data rate between the transmitter / receiver , we simulate the performance (quality of service) with different values of D , D varying between 1,5Gbps and 12Gbps,in terms of Q-factors illustration. (Fig IV.22)shows the results of Q-factor.

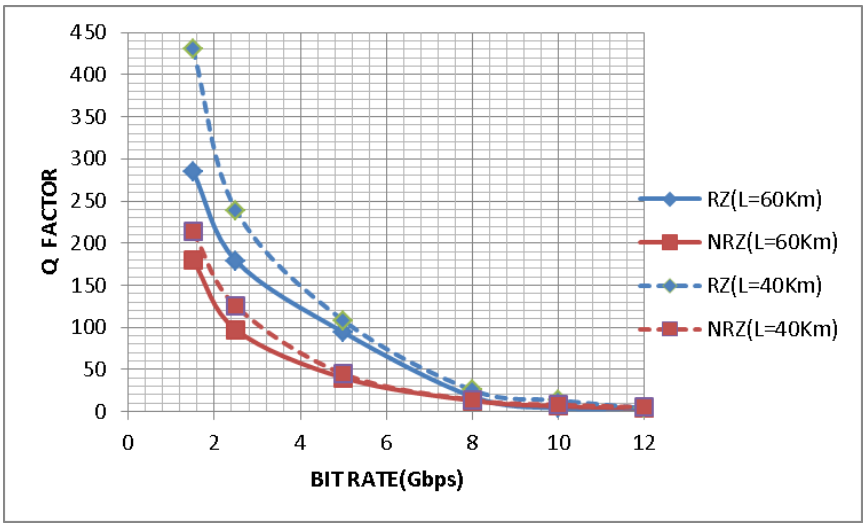
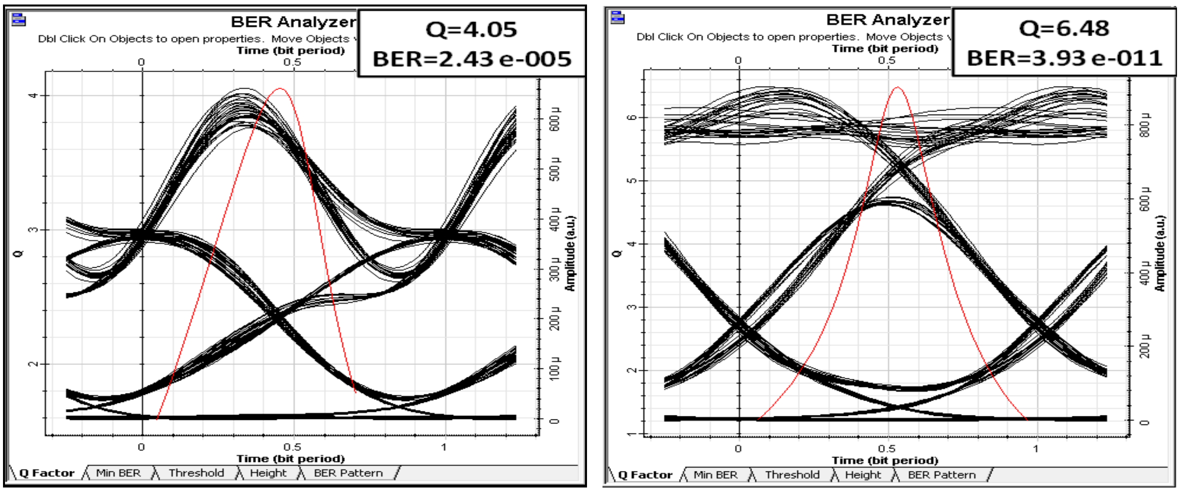


Figure IV.22 Q-factor *vs* Bit rate using RZ and NRZ modulations

This performance degradation is explained by increasing interferences in the propagation medium (channel) between the data bits, leading to poor detection of the receiver bits. (Fig IV.20) shows downlink eye diagram results when D is 10Gbps.As to (Fig IV.19), it shows Q-factor curves with L=60 km and L=40Km of optical fiber, P=6dBm and a number of user is 128 users who communicate at the same time. The illustration shows a decrease in signal quality when the bit rate increases and the BER increases. The output of the Q-factor is shown in (Fig IV .22). Obviously, for system performance, using RZ modulation is better, Comparing RZ with NRZ modulation reveals the RZ is more suitable for low bit rate than the NRZ modulation, obviously that 2.5 Gbps in RZ data format gives the best implementation then follow by NRZ format (for RZ, D must be less than 8Gbps for length L=60Km and less than 10Gbps for length L=40Km).For the eye diagram results, when the data bit rate is 10 Gbps and L equals to 60Km with RZ and NRZ see(Fig V.23 (*a* and *b*)).(for D=10Gbps for L=40Km using RZ Q=13,34and BER=5,81 e -41, and using NRZ for Q=8,23 and BER=7,578e-017). We conclude that RZ works in short distances, and it is better in law bit rate, this means that we can increase the distance in the system using RZ with law bit rate (for ex 1,5 Gbps and 2,5Gbps)

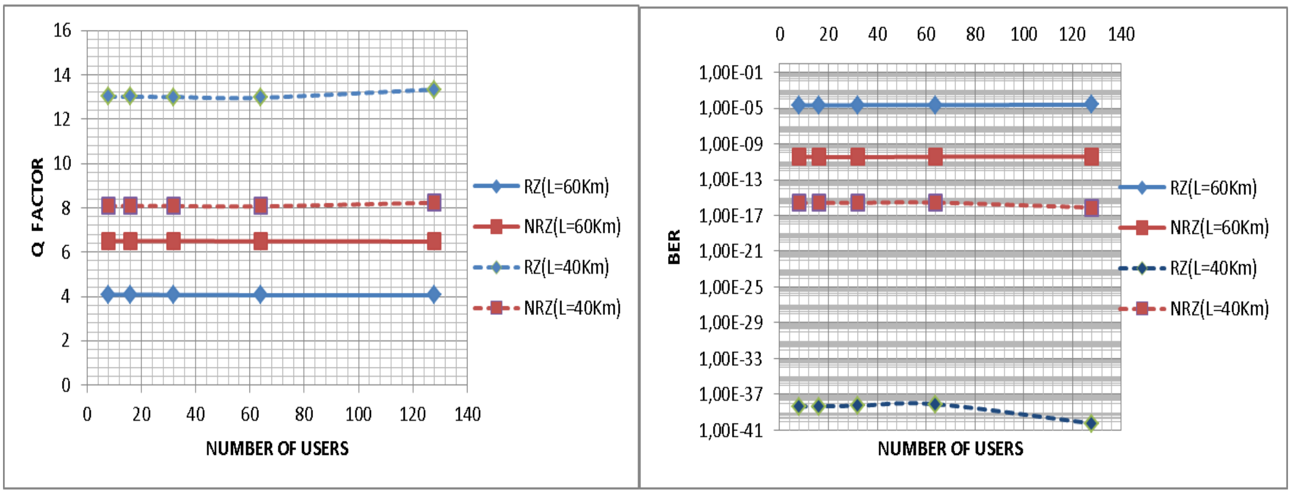


a) b)

Figure IV.23 BER analyzer showing Eye diagram of downlink (Q-factor in red line) , *a*) RZ,*b*) NRZ

IV.3.1.4 Impact of user's number

To assess the output effect of the number of subscribers, we evaluated the system architecture by measuring Q and BER values for different values of subscribers that interact at the same time. We looked at the Optical system data rate, D = 10Gbps, power P=6dBm and distance L=60Km and L=40Km. The results of the simulation are grouped under (Fig IV. 24).



a) b)

Figure IV.24 a)Q-factor and b)Log of BER *vs* users' number using RZ and NRZ modulations

Fig IV.24 show that the more the number of users who communicate at the same time increases, the more the performance of the system deteriorates due to the increased interference between data bits which leads to bad data detection. As a result, as the number of active users increases, the greater the interference and the more the performance (service quality) deteriorate. As illustrated in (Fig IV.25), using RZ modulation is best for the system performance for L up to 40Km, but NRZ modulation is better for the system for L beyond 40Km (for ex. 60Km).

IV.4. Numerical simulation of High Speed Optical Local Area Networks

To achieve a high-speed connectivity with large bandwidth, optical local area networks (OLANs) are among highly flexible technologies used in the field. OLANs have attracted more interest due to their data access security, and ability to support asynchronous and burst data transmission. This part describes model for optical LAN network system, and shows the influence of several parameters on the transmission quality [13]. This study allowed us to improve the service quality and the optical communication system performance.

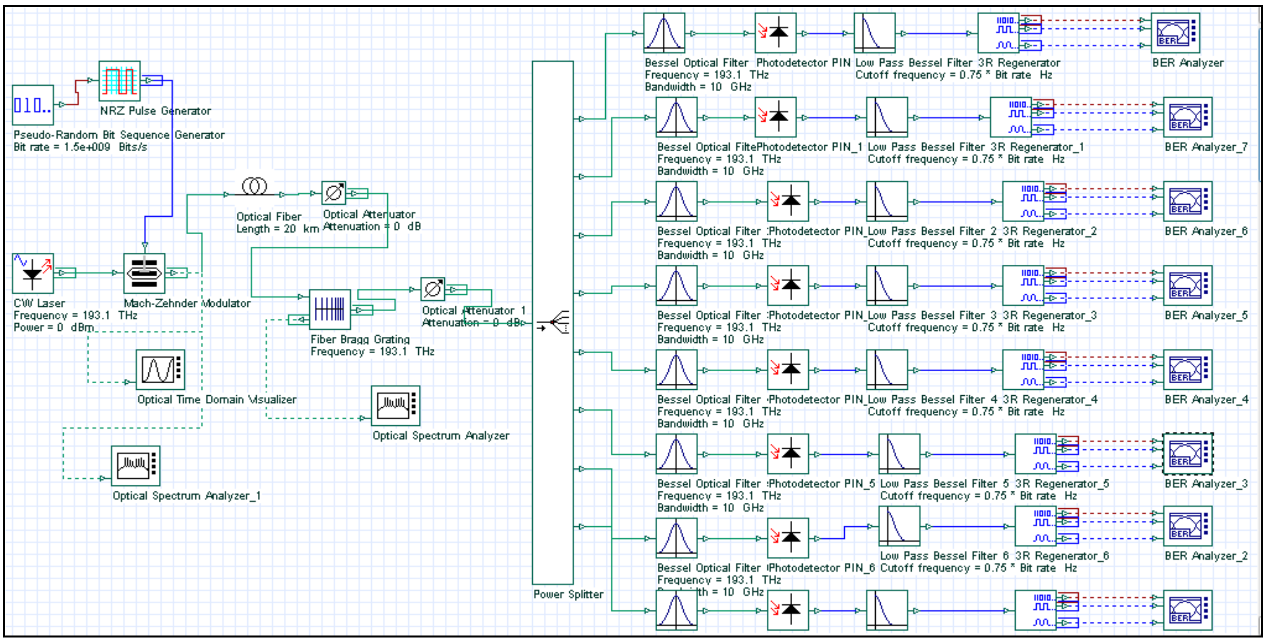


Figure IV.25 OLAN simulation setup

To implement effective optical network (Fig IV. 25) communication for large range, we aim here to meet the performance and quality requirements, and understand the concept of P2MP gigabit using OptiSystem. OLAN system consists of three blocks, where components and functionalities characterize the block.

IV.4.1. Transmitter section

The block has the role of transmitting a continuous optical signal and modulate it according to the binary data and the chosen format. In our system to study, the transmitter includes the following components:

- Continuous wave (CW) laser: an electroluminescent diode is used for broadband light source, whereas in CW lasers fields are intelligible momentarily.
- User Defined Bit Sequence Generator: To Generate the sequence of data bits to be transmitted.
- NRZ Pulse Generator: Pulse generator without zero return.
- Mach-Zehnder Modulator that control the optical wave amplitude, and burn the informative signal (electrical) on the light signal (Laser).

IV.4.2. Channel section

- Optical Fiber that represents the propagation medium of light (data) between OLT and ONT.
- Optical attenuator (fiber optical attenuator) reducing the optical signal power level in optical fibers in the free space. In an optical communication system, the optical power propagateing in transmission medium (optical fiber) could be calculated by this formula:

$$P(z) = P(0)e^{-\alpha z} \qquad \text{(IV.3)}$$

$$\alpha = \frac{1}{z}\ln\left[\frac{P(0)}{P(z)}\right] \qquad \text{(IV.4)}$$

$$\alpha\left(\frac{dB}{Km}\right) = \frac{10}{z} = \log\left[\frac{P(0)}{P(Z)}\right] = 4.343\alpha \qquad \text{(IV.5)}$$

Where, *P (0)*, *P(z)* and α are respectively the:
* Optical power at the origin (at Z=0),
* Power at a distance small z,
* Fiber attenuation coefficient, and α(*dB/Km*) is referred as the fiber loss (or fiber attenuation).

IV.4.3. Receiver section

Designing receivers is to receive desired efficient signals with a minimum BER, to achieve the customer's requirement. Such design comprises of:

- PIN Photodetectors that detect optical signals and convert them into electrical signals.
- Low Pass Bessel Filter used to minimize the output noise of the PIN.
- 3R Regenerator making it possible to analyze/calculate the BER.
- BER Analyzer that displays Q-factor and BER values, and Eye Diagrams.

IV.4.4. Factors influing optical LAN networks

To examine and assess the exhibition of optical communication frameworks, BERs and Q-factors (signal-to-noise ratios) of the optimal decision point, are effective methods. BER estimation methods compare bits generated by a binary signal and the signal received [86]

IV.4.4.1. Power impact

To evaluate the optical power impact, we have simulated the performances (quality of service) in terms of the two factors Q and BER with different values of P. If we Assume that the P value varies in the range -3 to 12dBm, and we consider the data rate of the PON system, D = 10 Gbps, number of users ONT=32 communicating simultaneously and distance L=15 km. Q-factor and BER results are shown in (Fig IV. 23), below.

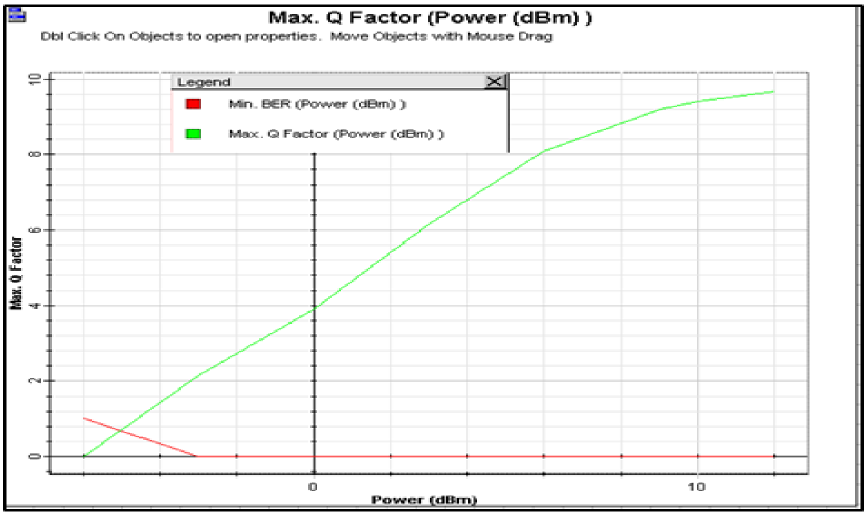
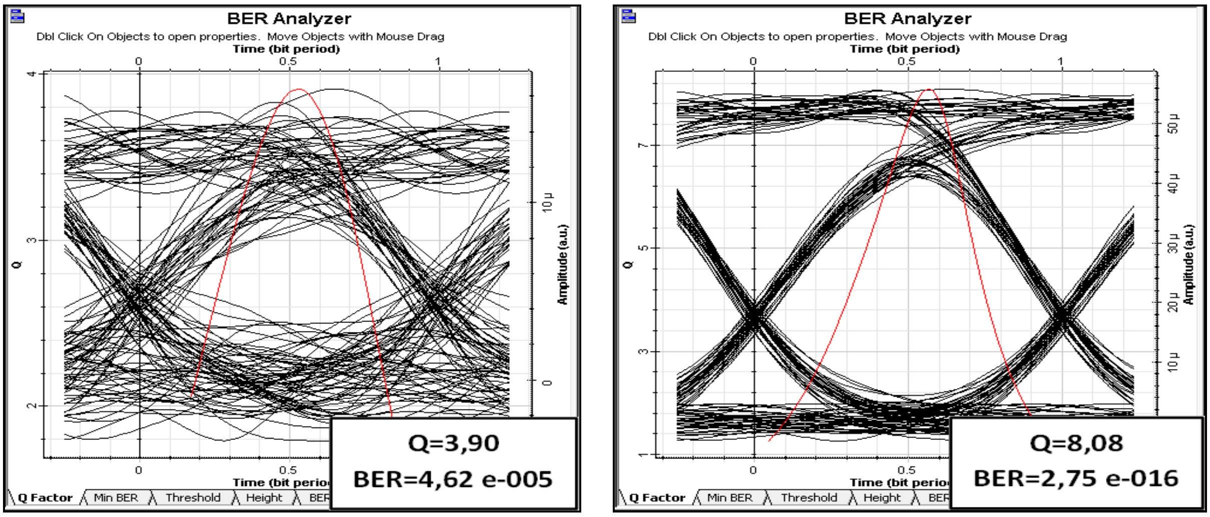


Figure IV.26 BER and Q-factor *vs* Power

From (Fig IV.26), we can notice that when the power increases from -3dBm to 12dBm, which means that the receiver receives more power, the values of Q and BER are improved and consequently the performances of the system are improved. Note that P ought to be more prominent than 3dBm to ensure BER under 10^{-9} and Q-factor great than 6 (requirements of optical networks).

(Fig IV.27 (*a* and *b*)) show the consequences of eye graphs (eye diagrams) of downlink when P is 0dBm and 6dBm, respectively. The slope of slant edge of eye graph speaks to the affectability to time mistake of framework.

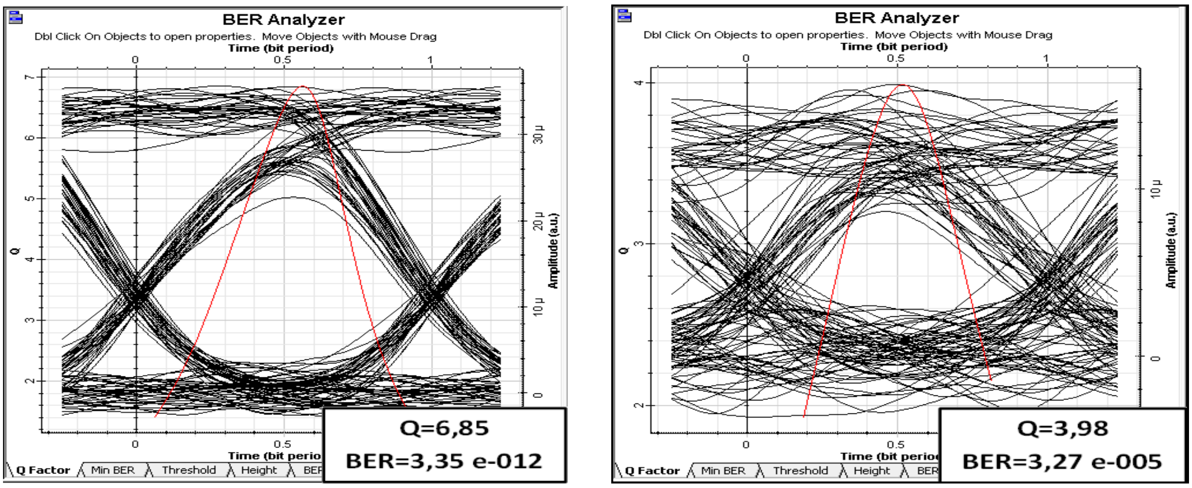


a) b)

Figure IV.27 BER analyzer showning Eye diagram of downlink (Q-factor in red line) with: a) P=0dBm; b) P=6dBm

IV.4.4.2. Impact of transmission distance

In the following simulation, we assume that P=3dBm, D=10Gbps and number of users ONT=32. (Fig IV.28 (*a* and *b*)) shows how eye charts of downlink changes with fiber length of 10km and 30km, respectively. Transmission separation (for example L) fluctuates from 5 km to 70Km, the aftereffects of Q-factor and BER are appeared in Figure IV.29. It is worth noting that the more transmitter/receiver distance increases, the more Q-factor of the reception decreases gradually, due to the loss of fiber. So it would be necessary to take into account the distance in a transmission to have an optimal quality of signal in reception.



a) b)

Figure IV .28 BER analyzer showning Eye diagram of downlink (Q-factor in red line) with a)L=10km; *b*)L=30km, D=10Gbps and ONT=32 as users number.

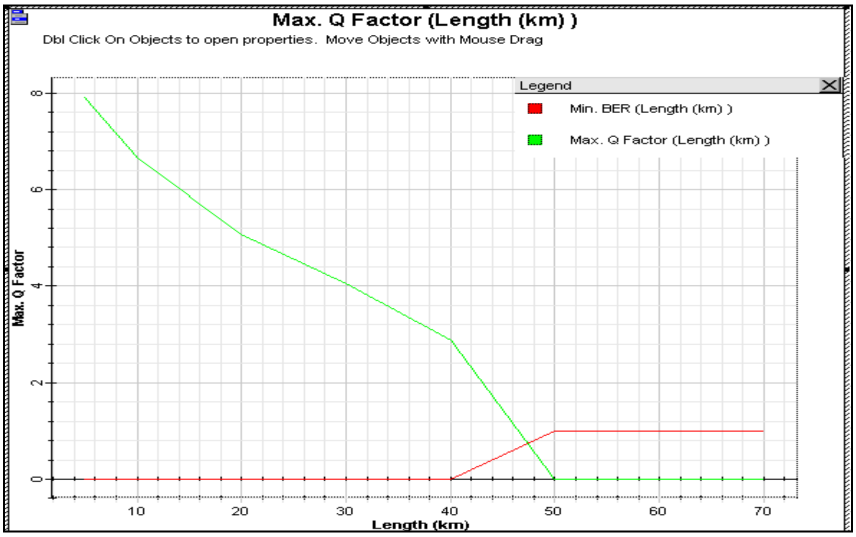


Figure IV. 29 BER and Q-factor vs. Length

It likewise infers that L ought to be under 15 km to fulfill the necessity of BER (<10^{-9}) and Q>6. Optical intensifier (amplifier) might be utilized to repay the loss of optical flag and consequently increment the transmission length.

IV.4.4.3. Impact of data rate

To evaluate the impact of data rate between OLT-ONT, we simulate the performances (quality of service) in terms of the two factors Q and BER with different values of D. (Fig V.30) shows the Q-factor and BER results. As for (Fig IV.30), it shows BER and Q-factor curves obtained with L=15km of optical fiber, P=3dBm and a number of users ONT=32 users that communicate simultaneously. We can notice that the BER increases and the Q factor decreased (i.e. performance degrades) as the D rate increases. This performance degradation is explained by increase of the interferences between the bits of the data in the propagation medium (channel), which leads to poorly detect the bits of the ONT. (Fig IV.31 (a and b)) show results of eye diagrams of downlink when D is 10Gbps and 20Gbps, respectively.

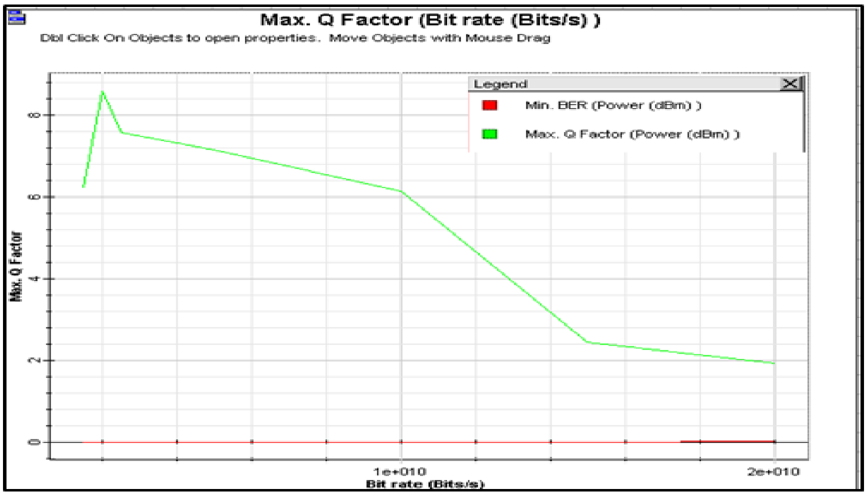
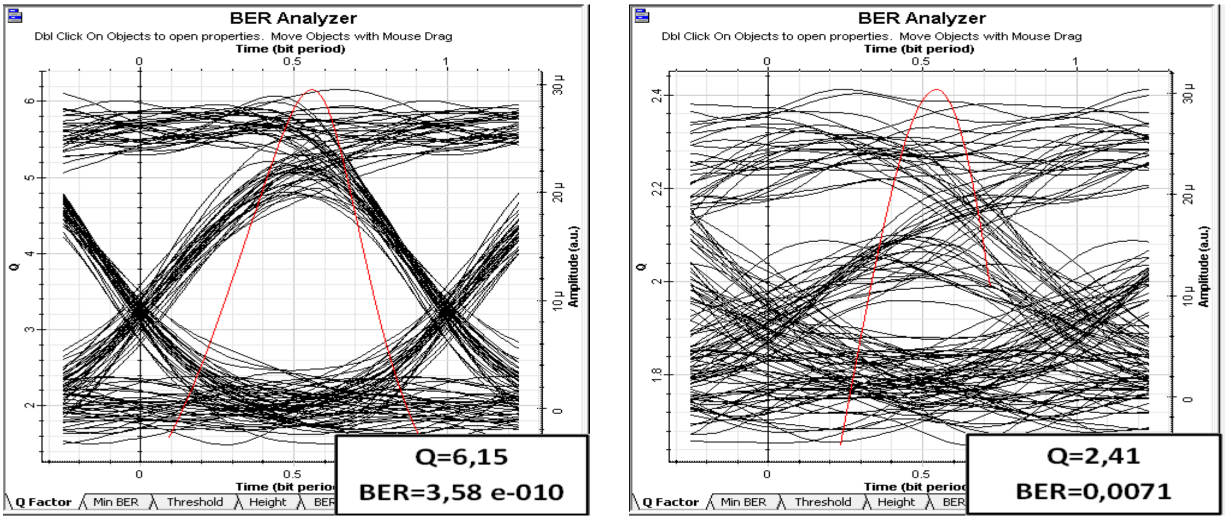


Figure IV. 30 BER and Q-factor vs. Bit rate



a) b)

Figure IV. 31 BER analyzer showning Eye diagram of downlink (Q-factor in red line) with: (a) D=10Gbps; (b) D=20Gbps

IV.4.4.4. Impact of number of users ONT

In order to evaluate the performance impact of the number of subscribers, we have tested the OLAN architecture by calculating Q and BER values for different subscriber values that communicate simultaneously. We considered the data rate of the Optical LAN system, D=15Gbps, power P=3dBm and distance L=15Km. The simulation results are grouped in (Fig IV.32) (detailed parameters values shown in Table IV. 1).

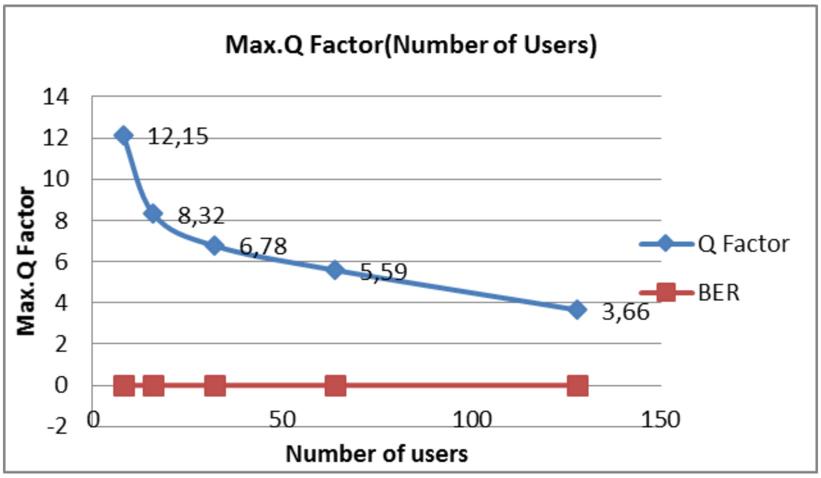


Figure IV. 32 Q factor and BER vs. Number of users

Table IV.1 Q-Factoer and BER vs number of ONT

Number of ONT	Factor Q	BER
8	12.15	2.82E-34
16	8.32	4.16E-17
32	6.78	5.72E-12
64	5.59	1.06E-8
128	3.66	0.001

The table IV.1 and (Fig IV.32) show that the more the number of users ONT who communicate simultaneously increases, the more the system performance deteriorates because of the increase in the interference between the data bits which leads to bad data detection. As a result, as the number of active users increases, the more interference increases, and the more the performances deteriorate.

IV.5. Performance Comparison of APD and PIN Photodiodes using RZ and NRZ

In this part, we have studied the quality factor (Q), bit error rate (BER) and eye diagram of a gigabyte passive optical network (GPON) used modulation formats, and compare Q, BER performance. Analysis performed for non return to zero (NRZ) and RZ line codes by using avalanche photo diode (APD) and P-Insulator-N (PIN) photodiod receivers, revealed an improved Q-Factor by changing encoding techniques at different length optical fiber, bit rate, CW laser power and number of users [27].The system performance is measured in terms of Q-factor, BER and eye diagram by varying the system component with and without EDFA, The network layout is designed and simulated with Optisystem 7 software.

IV.5.1 FTTH-GPON Systems

Optical line terminals (OLTs), optical splitters and optical network terminals (ONTs) are the three main components of fiber to the home (FTTH)-GPON access network (Fig IV.33):

- OLT is the main element of a network, usually placed in the local exchange, and the engine driving the FTTH-GPON system. Traffic planning [87].
- Splitter having one input from port and multiple output ports is passive because it requires no external energy source other than the incident light beam. It is only add loss and broadband, mostly due to the fact that it divides the input (downstream) power. Such loss is called "splitter loss" or "splitting ratio"[87].
- ONT, deployed at the customer premises, is connected to the OLT by means of optical fiber and no active elements are present in the link [87].

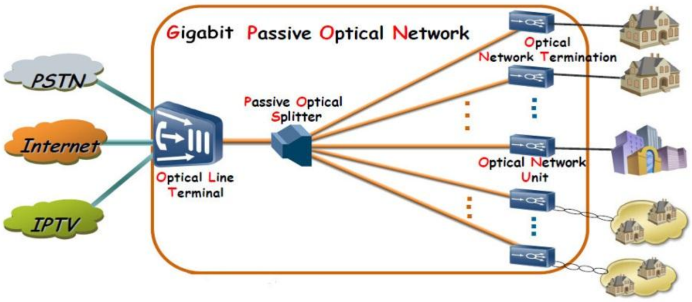


Figure IV. 33 FTTH-GPON network [28]

The system could degrade becoming weaker in the channel, and signal is hence attenuated when some part of this is lost, and we need for that to use EDFAs. Using Optisystem software different modulation formats have been made, such as RZ and NRZ, and a comparison between both photodiodes APD and PIN photodiodes has been here performed [29].

EDFA

Because of its high gain and low noise feature, a great preference is given to the EDFA that enhances the quality of the signal and it helps to encounter the problems like attenuation and distortion, due to the used doping material: erbium (Er). EDFA has two bands named as L-Band

and C-Band, which are very commonly used these days, and a uniform gain at the wavelength range of 1550nm, hence it is the most suitable amplifier for this wavelength [29].

PIN Photodiode

PIN consists of three zones: the first zone in order to create a hole excess is called as P-doped, the second zone has an intrinsic region called absorption zone and the third zone is N-doped which creates an electron excess [88].

APD Photodiode

The avalanche effect is used to multiply the electrons in a photodiode. Such effect is used to increase the electrical signal power by generating several photoelectrons.[55] APDs are widely used in laser-based fiber optic systems to convert optical data into electrical form. They are high-sensitivity, high-speed semiconductor light sensors [54].

IV.5.2. Q-Factor and BER of GPONs

The study of Q-factor and BER of GPON using Optisystem is summarized in (Fig IV. 34 and 35) showing an EDFA schematic design in GPON systems that consists of :

- **Transmitter section :** including a pseudo random bit sequence generator (PRBSG), a continuous wave (CW) laser whose frequency and input power 6 dBm are respectively 193.1THz, an NRZ pulse generator (PG) and a Mach-Zehnder modulator
- **Channel section :**Optical fiber with length and attenuation of 100Km and 0.2dB/Km and an EDFA whose length is 5m.
- **Receiver section** : which consists of a Bessel optical filter whose frequency and bandwidth of 193.1THz and 10GHz respectively, a PIN photo- detector, a low pass Bessel filter (LPBF), with a Cut off frequency of 0.75*Bit, a rate and 3R Regenerator, and a BER Analyzer.

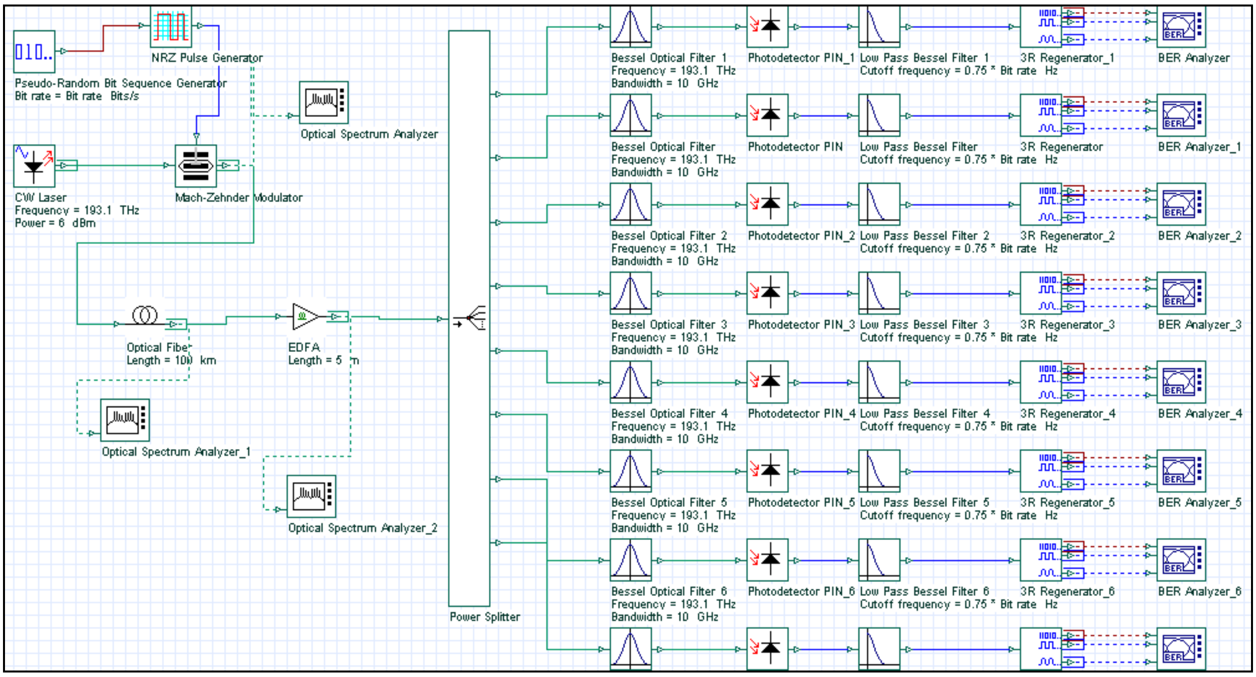


Figure IV. 34 FTTH-GPON simulation setup

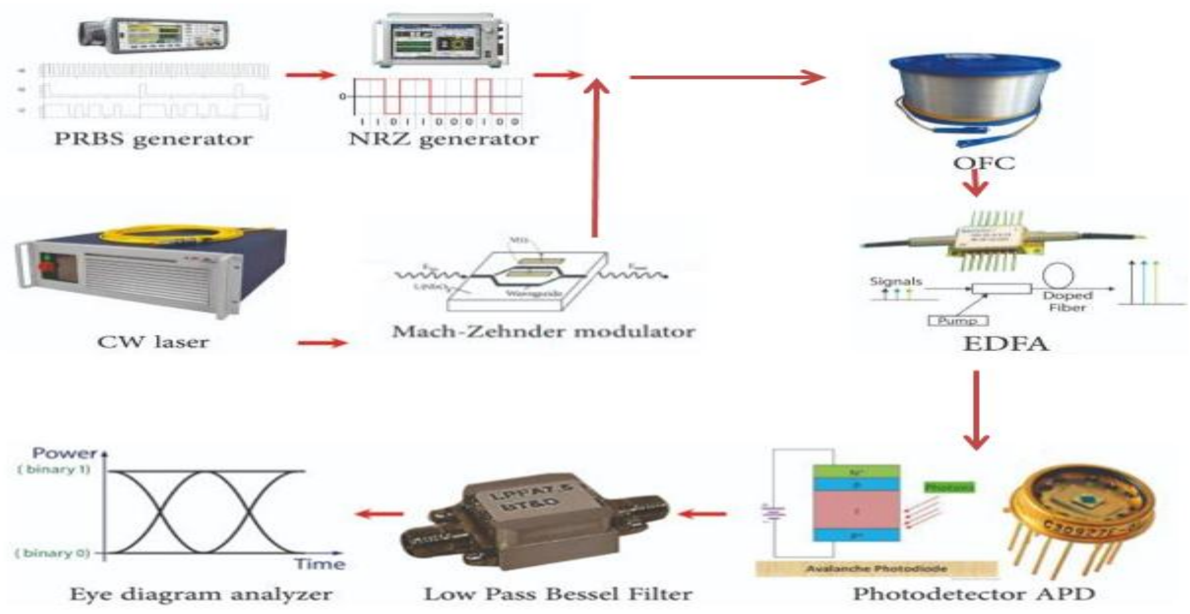
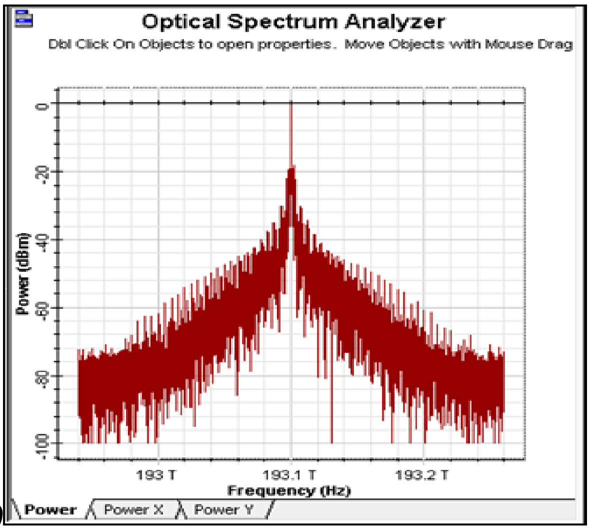
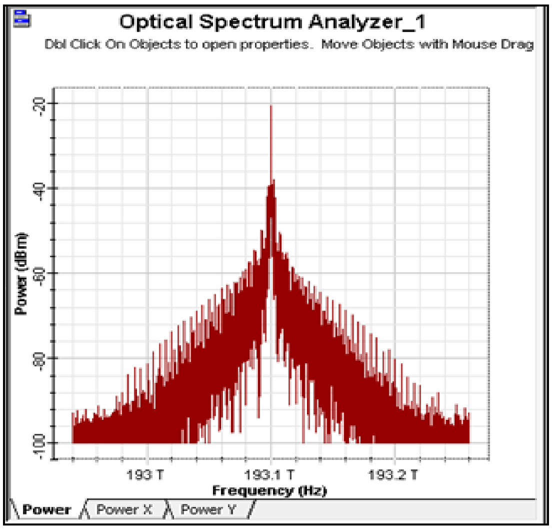


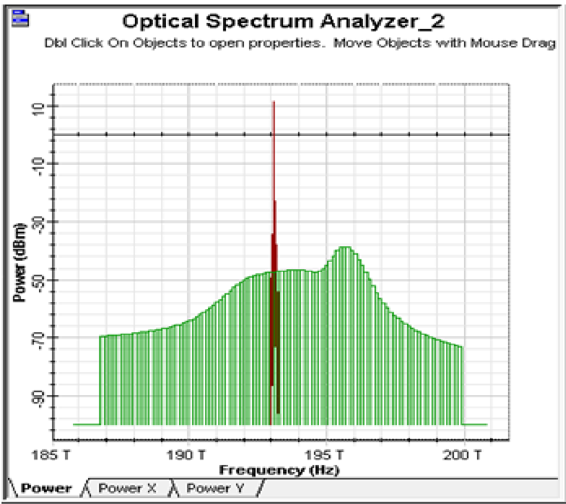
Figure IV. 35 Simulation model design.

IV.5.3 GPON with and without EDFA(8 users)

Fig IV. 36 shows the results of the multiplexer output which power is 0 dBm (*a*), optical fiber output whose power is -20 dBm (*b*), and EDFA amplifier output which is maximum value 0 dBm, but inversely in terms of noise (Fig IV.36(*c*)). The green curve in the graph represents the noise, while the red one shows the sample wavelength. Analyzing results, it can be concluded that EDFA should be used to compensate the loss of optical signal to increase the transmission length.

a)


b)




c)

Figure IV.36 Optical Spectrum Analyzer *a*) Multiplexer Output Power, *b*) Optical fiber Output, and *c*) EDFA Output.

In this model we are analyzing the Q-factor and BER by varying fiber length between 20 Km and 200Km (Fig IV.37). As appearing (Figs IV.37 and 38), Q-factor and BER performance by using EDFA is better than without using it.

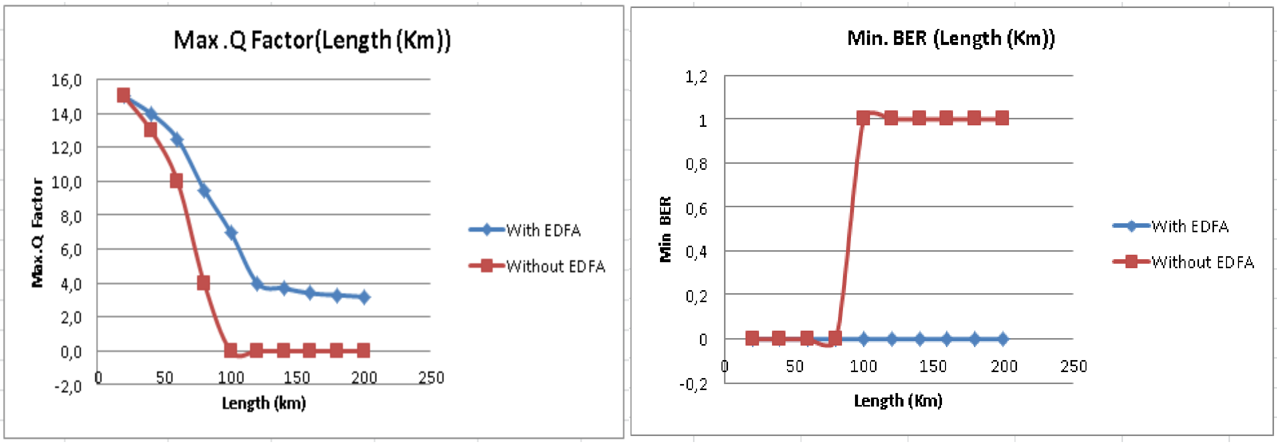
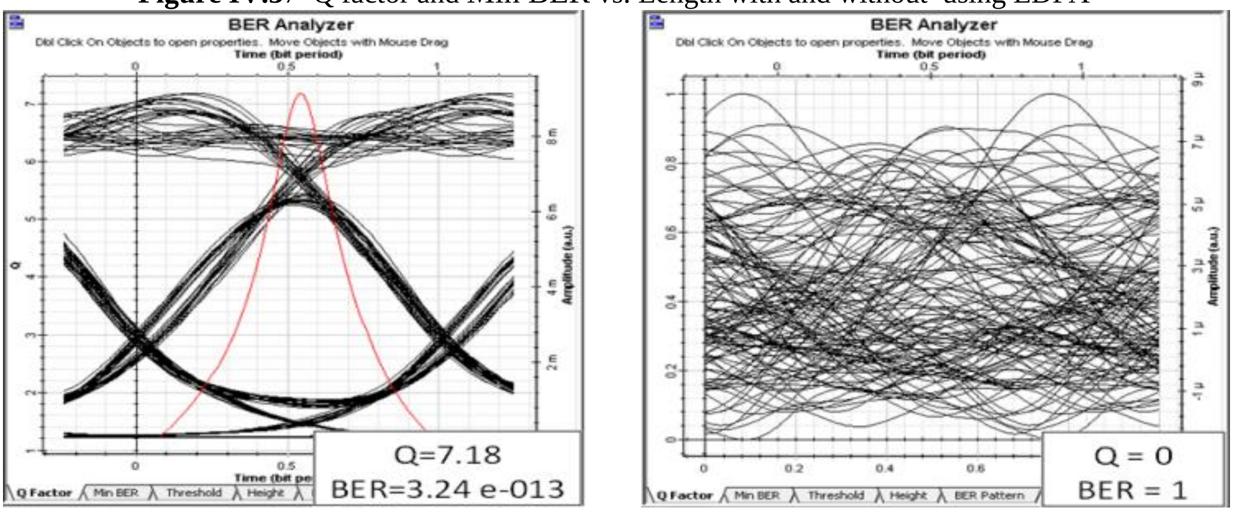


Figure IV.37 Q factor and Min BER vs. Length with and without using EDFA



a) *b)*

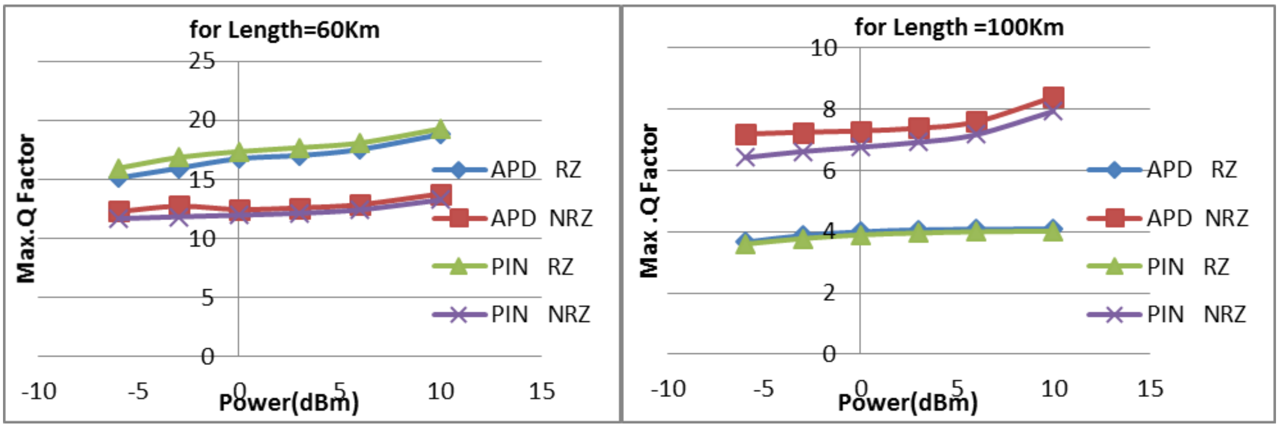
Figure IV .38 Eye diagram of downlink shown in BER analyzer (the red curve shows Q-factor) for L=100Km (*a*) with EDFA, (*b*) without EDFA.

IV.5.4 GPON with EDFA (32 users)

Our model has analyzed the Q-factor and BER, using PIN and APD, and NRZ and RZ modulation formats.

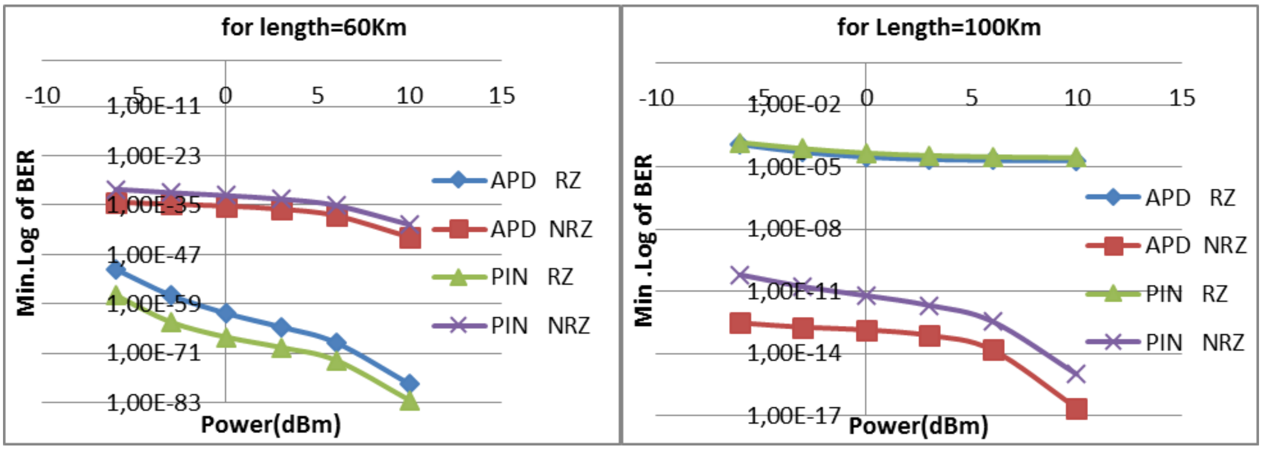
IV.5.4.1. Impact of CW laser power

To estimate the impact of power CW laser, simulated Q-factors and BER are shown for different transmitted powers (P) varying from -6 to10dBm, with a data rate set at 8Gbps for a link length of 60km and 100Km. For a users' number of 32 communicating simultaneously, the results show a signal quality increasing and a BER decreasing when P increases (Fig IV.39)and (Fig IV. 40).



a) b)

Figure IV .39 Max Q-factor vs Power with EDFA, for: *a*) L = 60Km, *b*) L = 100Km.using APD,PIN,RZ and NRZ



a) b)

Figure IV .40 Min Log of BER *vs* Power with EDFA, for (*a*) L = 60Km, (*b*) L = 100Km.using APD,PIN,RZ and NRZ

(Figs IV .39 and 40) show the BER and Q-factor performance of the modulation RZ and NRZ by using PIN and APD . One can clearly mention that using modulation RZ with APD and PIN is suitable for the system performance for length up to 60Km. For L farther than 60Km (for ex.,100Km) the modulation NRZ with APD and PIN is convenient for the system, and using APD is much better than PIN. As for the eye diagram results, when the data bit rate is 8Gbps, P is about 10dBm and L equals to 60/100Km with APD Photodiodes (see Fig IV.41 (*a -d*)).

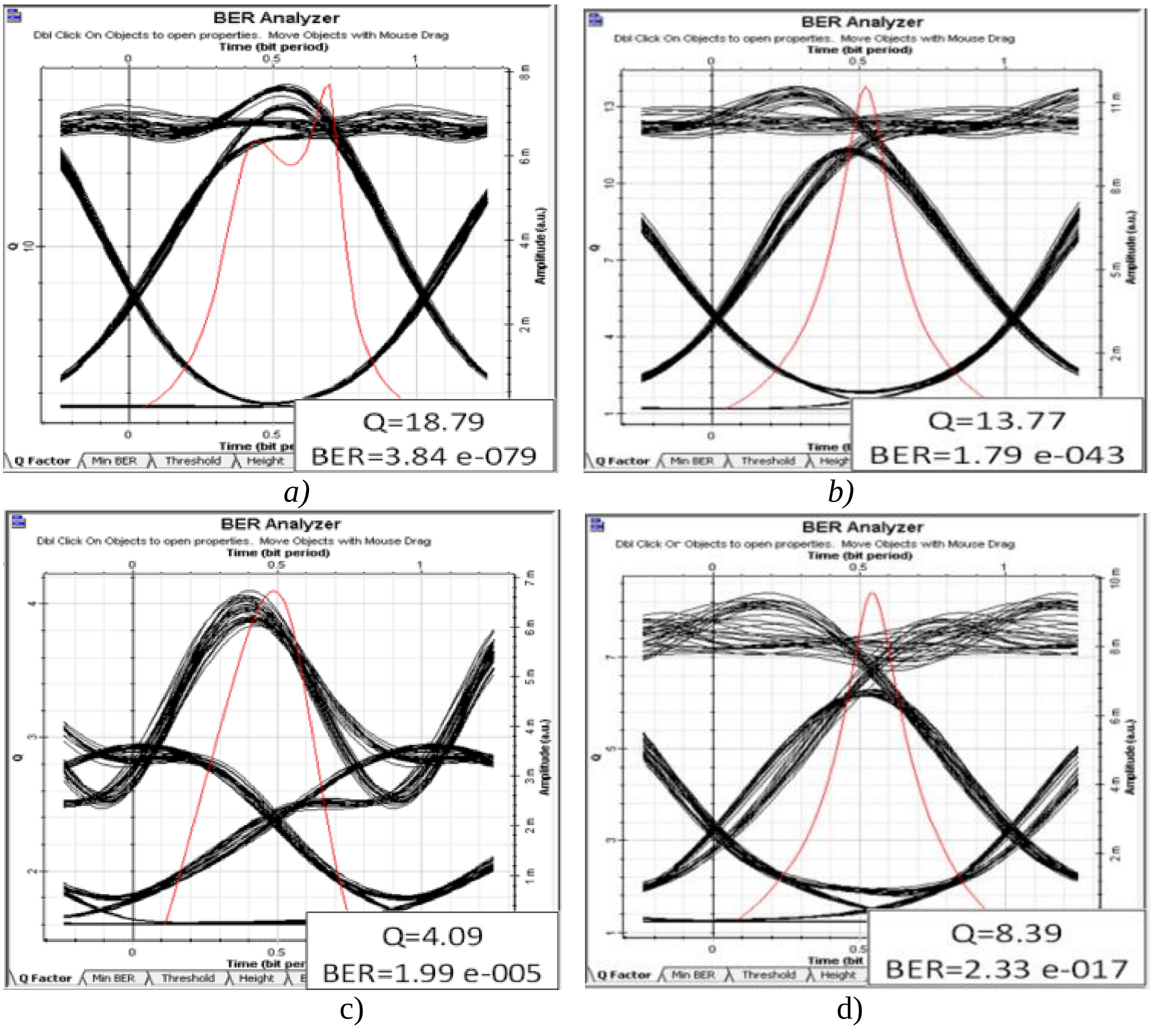


Figure IV.41 Eye diagram of downlink shown in BER analyzer (the red curve represents Q-factor) using APD with : *a*) RZ (60Km), *b*) NRZ(60Km), *c*) RZ(100Km), *d*) NRZ(100Km).

IV.5.4.2. Impact of transmission distance

In the following, we P=6dBm, D=8Gbps and users' number of 32, using PIN photodetectors, are assumed. (Fig IV.43 (*a* - d)) shows how eye diagrams of downlink changes with fiber lengths of 60 and 100km, respectively. With a transmission distance (i.e. L) varying between 10 and 200Km, the results of Q-factor and BER are shown in (Fig IV.42) .

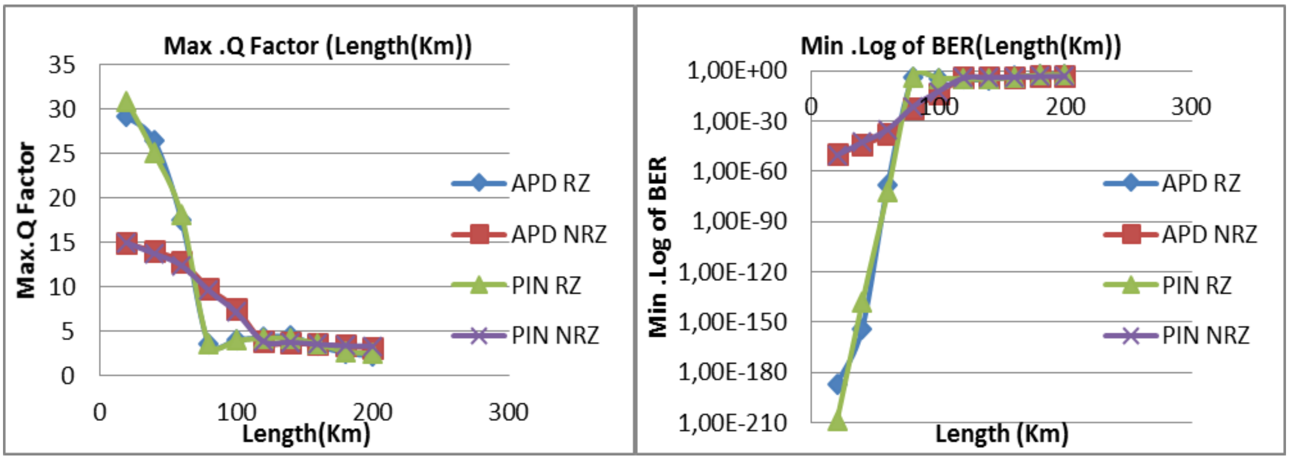


Figure IV. 42 Max Q-factor and Min Log of BER vs Length using APD,PIN,RZ and NRZ

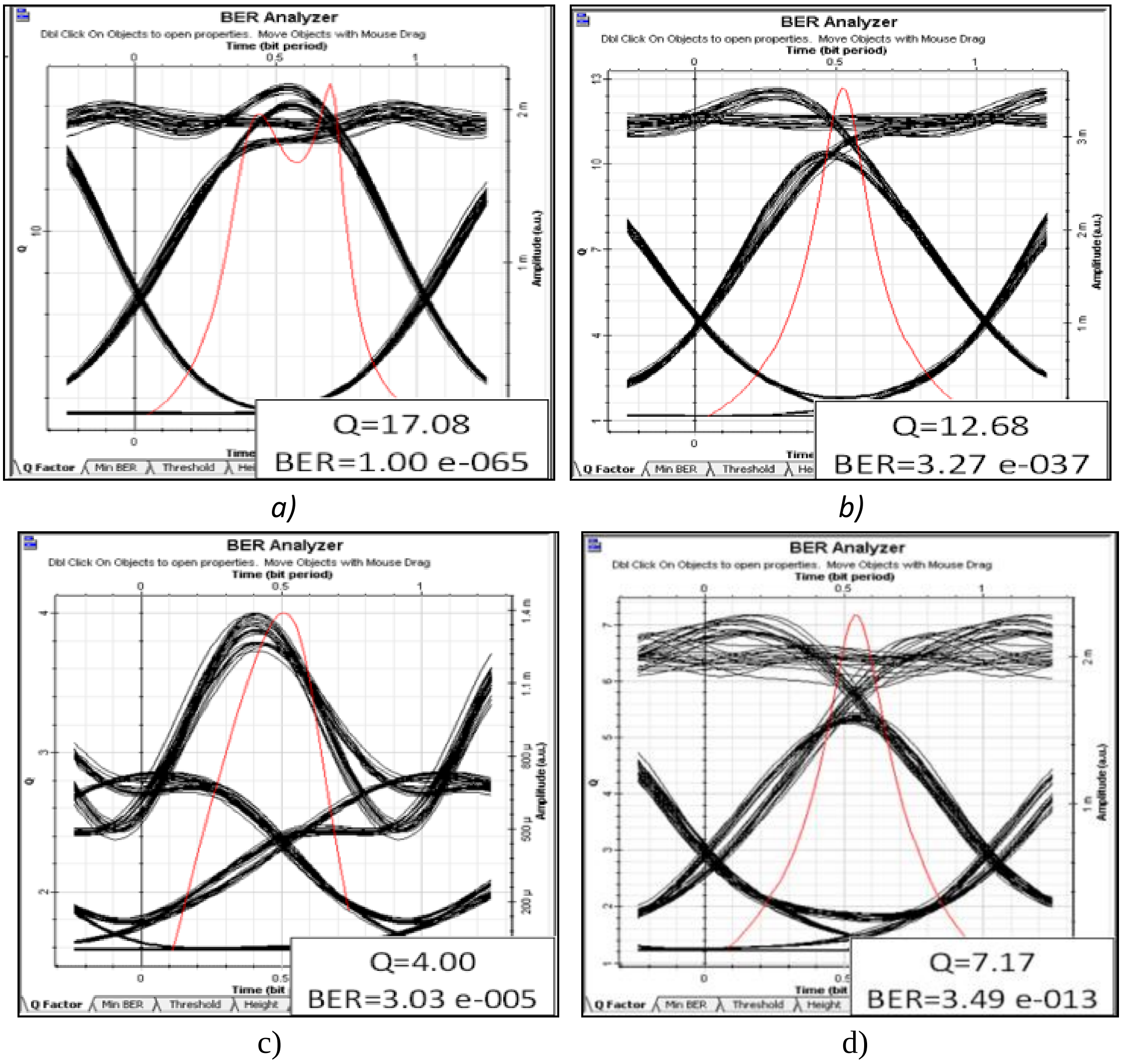


Figure IV .43 Eye diagram of downlink shown in BER analyzer (red curve represents Q-factor) with: *a*) PIN, *b*) RZ(60Km) NRZ(60Km), *c*) RZ(100Km), *d*) NRZ(100Km).

(Fig.IV.42 and 43) show that using modulation RZ with APD and PIN is better for the system performance for length up to 60Km. so for lengths beyond 60Km, the modulation NRZ with APD and PIN is more convenient for the system.

IV.5.4.3. Impact of Bite rate (D)

To evaluate the impact of data rate between the transmitter and receiver, we have studied the performances in terms of Q-factors and BER for different values of D and P of 6dBm. The results are shown in (Fig IV .44 and 45).

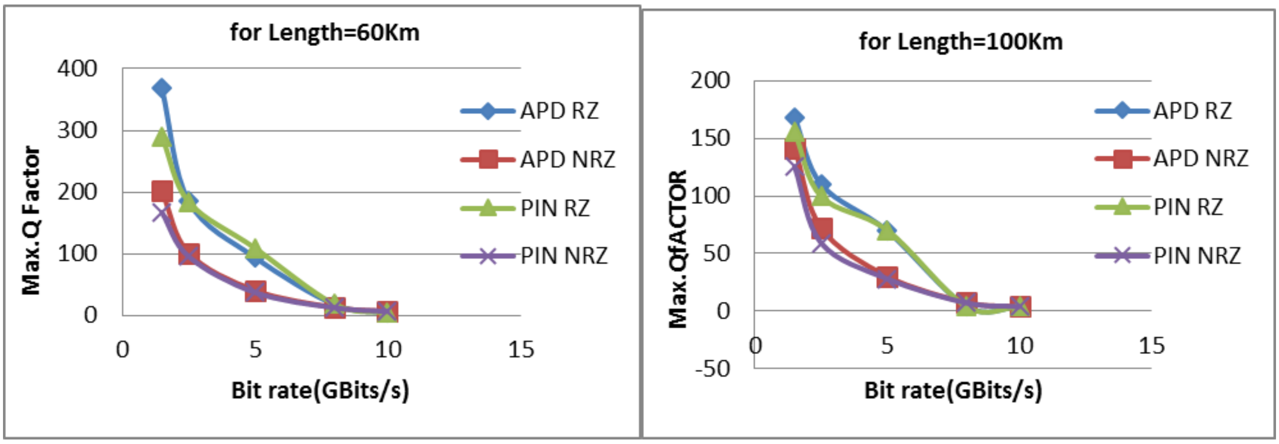


Figure IV.44 Max Q-factor *vs* D for L: *a*) 60Km, *b*) 100Km using APD,PIN,RZ and NRZ

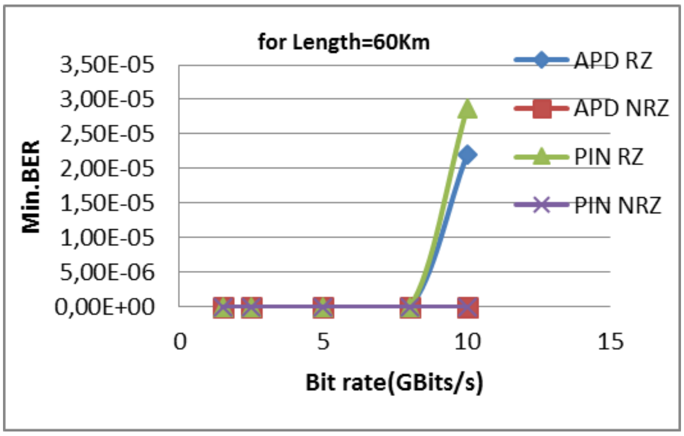
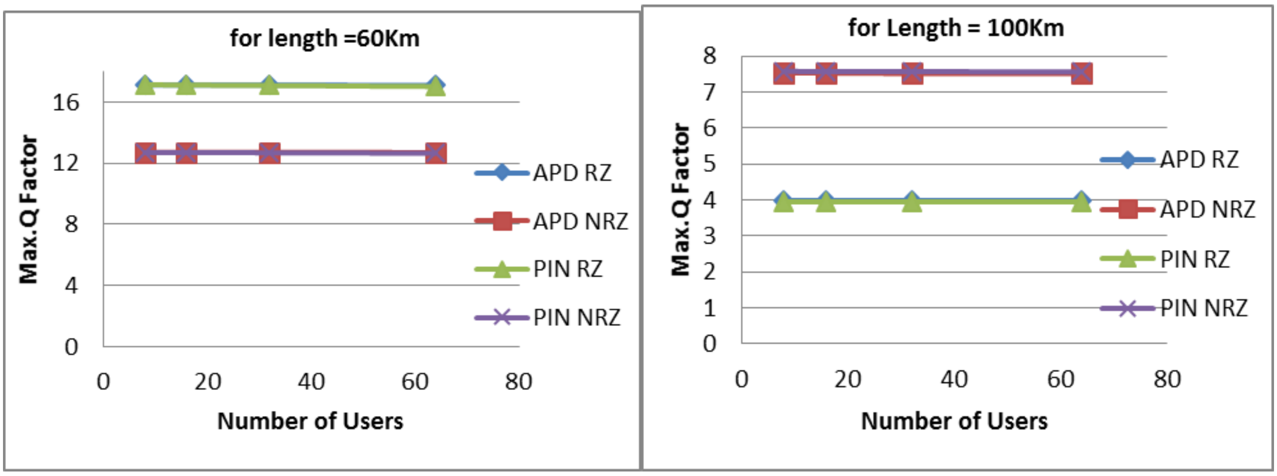


Figure IV.45 Min Log of BER *vs* D for L=60Km using APD,PIN,RZ and NRZ

Figs IV.44 and 45 show a decreasing of the signal quality when the bit rate increases and BER increases. The Q-factor and BER performance are shown in (Figs IV.44 and 45) One can clearly mention that using RZ modulation with APD and PIN is better for the system performance, and Q-factor performance of APD is higher than that of PIN. Comparing PIN with APD photodiodes reveals that the APD is more advantageous than the PIN photodiode for the low bit rate.

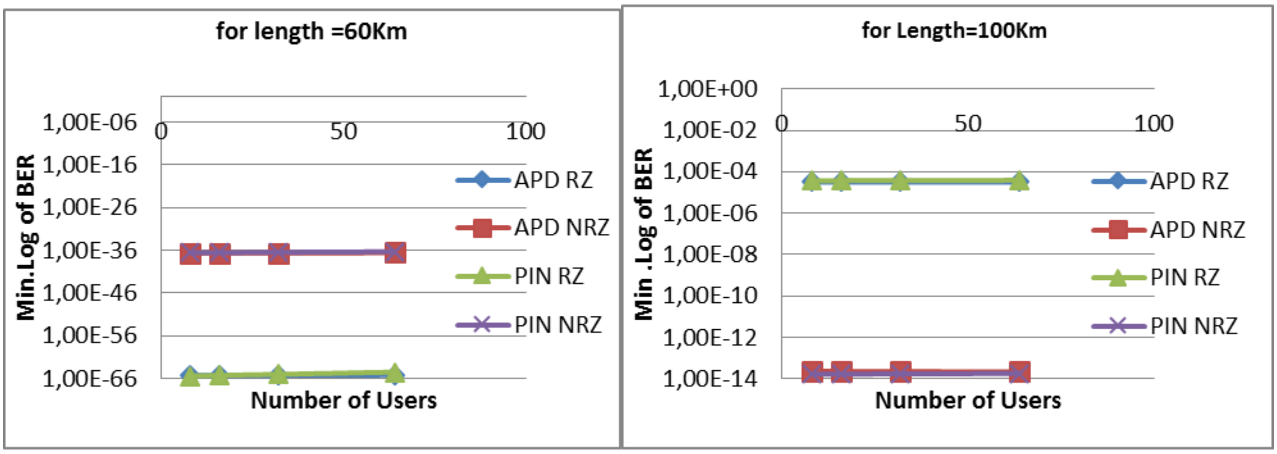
IV.5.4.4. Impact of number of users

To evaluate the performance impact of the number of users, we tested the GPON architecture by calculating Q and BER values for many subscribers simultaneously communicating. We considered the data rate D=8Gbps, power P=6dBm. The simulated results are shown in (Figs IV.46 and 47).



a) b)

Figure IV.46.Q-factor *vs* users' number for L: a) 60Km, *b*) 100Km using APD,PIN,RZ and NRZ



a) b)

Figure IV.47.Min Log of BER vs users' number for L:*a*) 60Km, *b*) L=100Km using APD,PIN,RZ and NRZ

As shown in (Fig IV.46 and 47), the use of modulation RZ with APD and PIN is better for the system performance for L up to 60KM, but for L beyond 60KM (for ex.,100Km) the modulation NRZ with APD and PIN is better for the system.

IV.6. The Performance Comparison of hybrid WDM/TDM, TDM And WDM PONs With 128 ONUs

We have simulated different unidirectional passive optical networks technologies such as wavelength division multiplexing (WDM), time-division multiplexing (TDM) and hybrid passive optical networks (PONs) with different users for varying fiber length, data rate, continuous wave laser power and number of users. Their performances based on the quality-factor (Q-factor) and bit error rate (BER) using OptiSystem software 7-0 with using an Erbium doped-fiber amplifier (EDFA) were compared. Our model used 16 and 128 users, where the performance of the unidirectional Hybrid WDM/TDM PONs with 4 wavelengths and 128 user systems have better high Q-factor and lower Bit Error Rate, compared to that of 128 user WDM PON and 128 user TDM PON systems [30].In this part, we have analyzed the performance that a hybrid PON with 128 users exhibits, with a bit rate of 2,5 Gbps per wavelength and a distance of 60 km using EDFA amplifiers. We have also compared a proposed hybrid PON system with TDM PON and WDM PON systems using EDFA, where Kheraliya *et al*. [89] proved that EDFA is best in terms of and Q factor at a reasonable long fiber. EDFA is the best in terms of BER and Q-factor versus Laser power at the transmitter for 32-Channel WDM System. This work deals with a performance comparison between TDM PON, WDM PONs and Hybrid WDM/TDM PONs, focusing on the downlink part only. It presents the transmission performance of a downstream link of these three distinguished networks, by using 16 and 128 users.

IV.6.1 TDM-PONS

TDM-PON, whose popular versions are Broadband, Ethernet and Gigabit-capable-PONs (BPON, EPON and GPON), applies TDM in PONs, while ONTs use the same wavelength and share a common line of transmission of optical fiber [40,41]. However, TDMA (time multiple access division) must be used to prevent collisions between traffic from various ONTs, where each user transmits information at a prearranged data rate within a specific assigned time slot [19,38]. TDM-PON is a law cost strategy for installation and maintenance,since the total system bandwidth is split into users for different time slots. However, it has limited capacity of users and a multipoint control protocol to control the message flow[43].

IV.6.2 WDM-PONs

Based on WDM, one of the most commonly used technology for high capacity optical communication systems, WDM-PONs can introduce good data transmission rate and large bandwidth [36,43, 90], WDM is an appropriate technique due to its high flexibility and higher level of information security[46,91], it can offer any advantages such as lower attenuation , easy management and upgradeability[20], where each communication channel having a special wavelength is multiplexed to a single fiber. Different wavelengths are demultiplexed at destination, and spatially separated to different receiver channels, so that WDM-PONs could use point-to-point and point – to - multipoint (or hybrid) communications [9,45] . Very commonly the complex wavelength division multiplexing is used in WDM-PONs. This technology is one of the most advanced systems used in the optoelectronics industry . The distance between channels is only 0.8 nm or 0.4 nm,as low as 0.2 nm (ultra- DWDM) theoretically [36].

IV.6.3 Hybrid WDM/TDM-PONS

In hybrid PONs (in which TDM and PONs are combined into a single passive optical network) the advantages of TDM PON's resource sharing are used to allow WDM PON's platform cost-efficient and high energy capacity to meet future bandwidth demand [9, 38]. In hybrid WDM/TDM-PONs, considered to be the key solutions for the next generation of PONs, offering high bandwidth and high use of resources [50], the high split ratio that TDM-PONs provide and the large number of wavelengths they offer are joined into one hybrid [92,93].

IV.6.4 Unidirectional TDM-PONS

These are PONs with only the downstream transmission. (Fig IV.48) shows a simulation diagram for unidirectional TDM PON with 16 users by using EDFA (with a fiber length L of 5m), where a power splitter is used to receive and separate the users' signals. OLT plays the role of a transmitter block. As for the receiver block, it consists of ONT, a 3R regenerator and a BER analyzer. The unidirectional TDMPON has been simulated using the wavelength 193,1THz for different fiber lengths. Data signal are generated at a data rate of 5 Gbps and CW laser power of 6dBm.

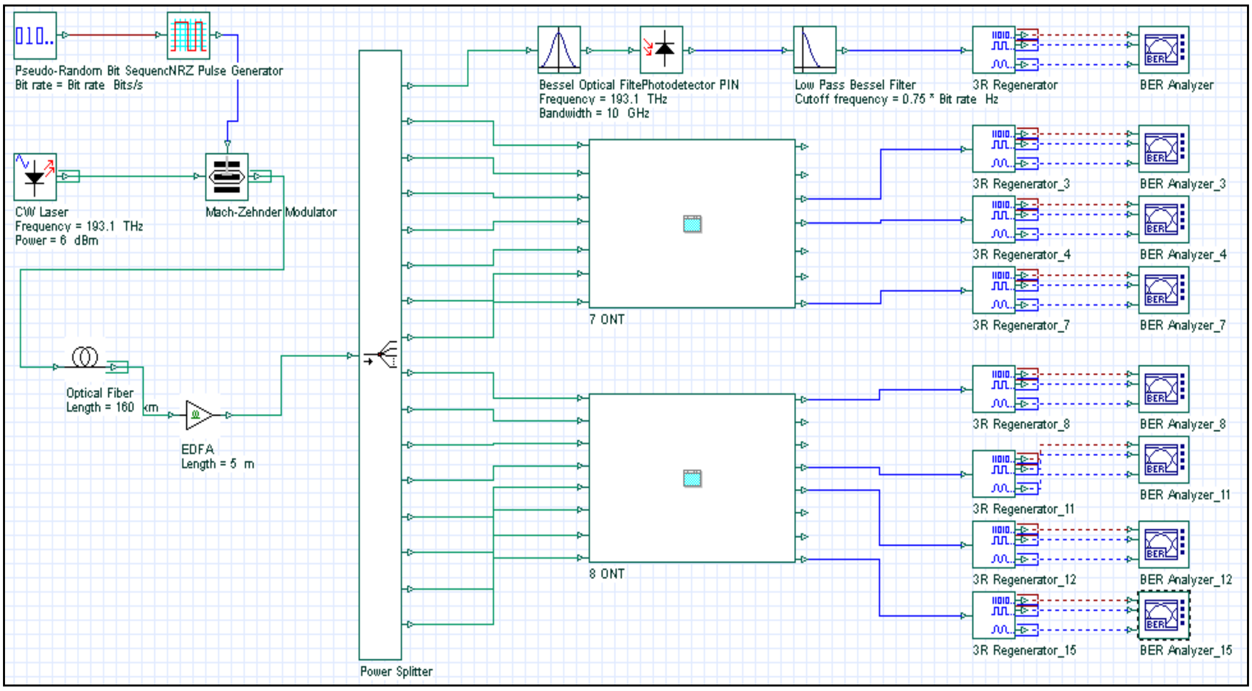


Figure IV.48 TDM-PON simulation setup.

IV.6.5 Unidirectional WDM-PONs

Our unidirectional WDM-PON is a PON with the downstream transmission using EDFA (L=5m). (Fig IV.49) gives an unidirectional WDM-PON simulation setup for with 16 users, where WDM-MUX is used to separates all wavelengths, using the frequency and frequency spacing 193,1THz and 100GHz, respectively. An input power of 6 dBm and data rate about 5 Gbps are used, with different fiber lengths. To combine signals/relay them as a single signal through optical fibers, WDM-MUX/DMUX are used at OLT, and to isolate all wavelengths respectively .

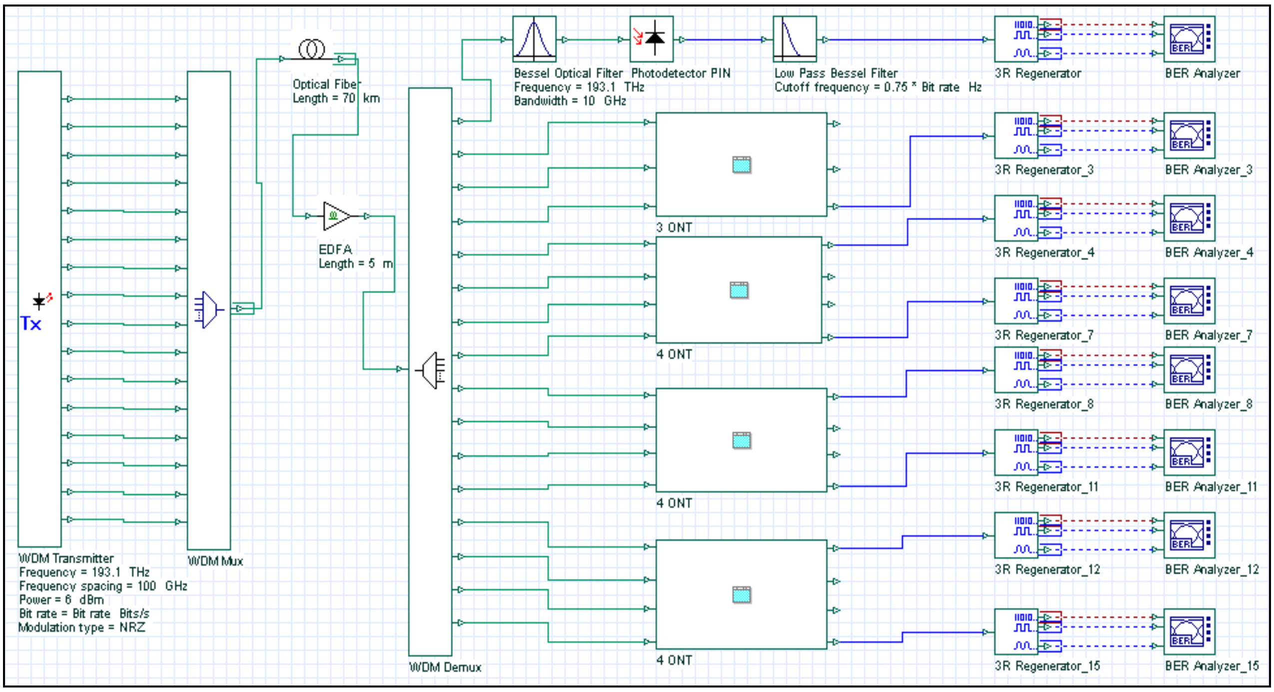


Figure IV.49 WDM PON simulation setup.

IV.6.6 Hybrid WDM/TDM-PONs

A block diagram of simulation setup for hybrid PONs (using 128 users) using OptiSystem is shown in (Fig IV.50). This central office system consists of four(4) OLTs, where light sources emit at different frequencies.Frequencies at OLT_1, OLT_2, OLT_3 and OLT_4 are respectively 193.1, 193.2, 193.3 and 193.4THz. Signals were combined together by a WDM-MUX for transmission over the fiber. At the remote node these signals were separated out using a WDM-DEMUX. Then, power splitters were employed to broadcast the signal to ONUs. Here, four power splitters were used with a splitting ratio of 1x4. A hybrid WDM/TDM PON consists of 16 ONTs, with an EDFA amplifier, a data rate D=5Gbps and a CW laser power (P) of 6dBm. Since BER and Q-factor are the most commonly used performance parameters, they were adopted as key-factors for this study. The first, Q-factor, an argument to the normal error function to calculate the second (BER):

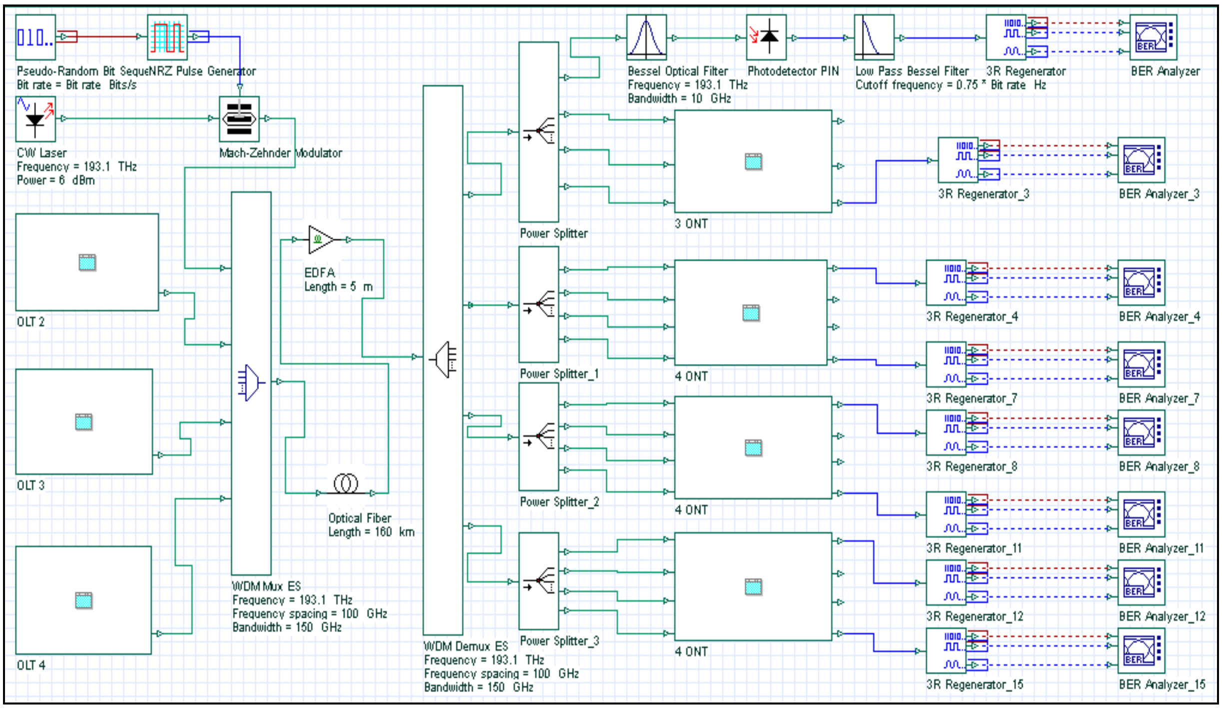


Figure IV.50 Hybrid WDM/TDM PON simulation setup(16 users)

IV.6.7 WDM PON, TDM PON AND Hybrid WDM/TDM PONs with and without EDFA

The proposed models for WDM PON, TDM PON and Hybrid WDM/TDM-PONs are integrated (with and without EDFA) and simulated using Optisystem, involve the following parameters: Bit Rate of 5 Gbps, EDFA length equals to 5 m, CW laser power of 6dBm, number of users of 16, and frequency of 193.1THz with 100 GHz (0.8 nm) as a channels spacing (for WDM-PONs-and Hybrid WDM/TDM PONs). The results are shown in (Fig IV.51).

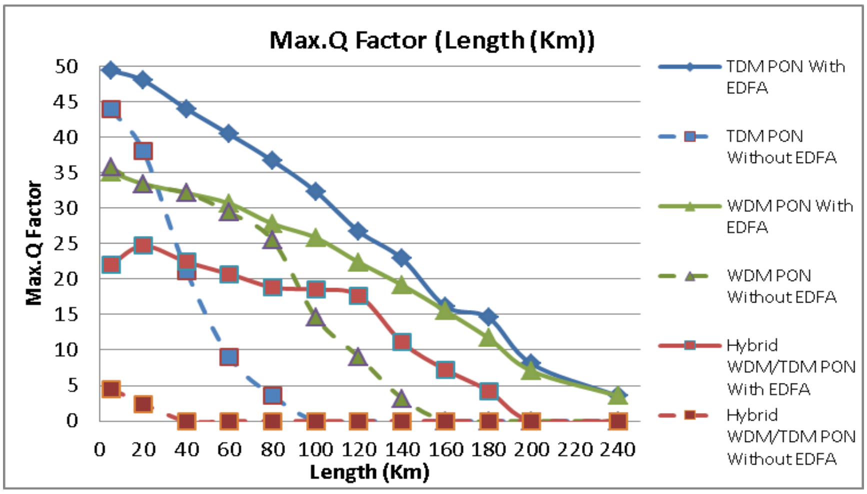


Figure IV.51 Hybrid WDM/TDM WDM PON and TDM-PONs in both cases.

It can be clearly seen (from Fig IV.51) that WDM/TDM-PONs and hybrid WDM/TDM-PONs integrated with EDFA give optimized Q-factor and BER, so that Q-factor was 7.03 for WDM-PONs integrated with EDFA, however, without EDFA it was 0 for a fiber length of 200 Km. For TDM-PONs, Q-factor was 8.04 for TDM-PONs with EDFA, while it was 0 without EDFA for for the same fiber lentgh. For hybrid WDM/TDM-PONs, Q-factor was 7.24 for hybrid WDM/TDM-PONs with EDFA, while for without EDFA it was nul for a 160 Km fiber length, which means that Q-factor performances by using EDFA are much better than without using it.

IV.6.8 WDM, TDM-PONs and Hybrid WDM/TDM-PONs by using EDFA

The proposed models architecture of hybrid PONs is designed for 128 subscribers (Fig IV.49), and 128 users for WDM-PONs with a channels spacing of 25GHz (0.2nm), and TDM with 128 users.

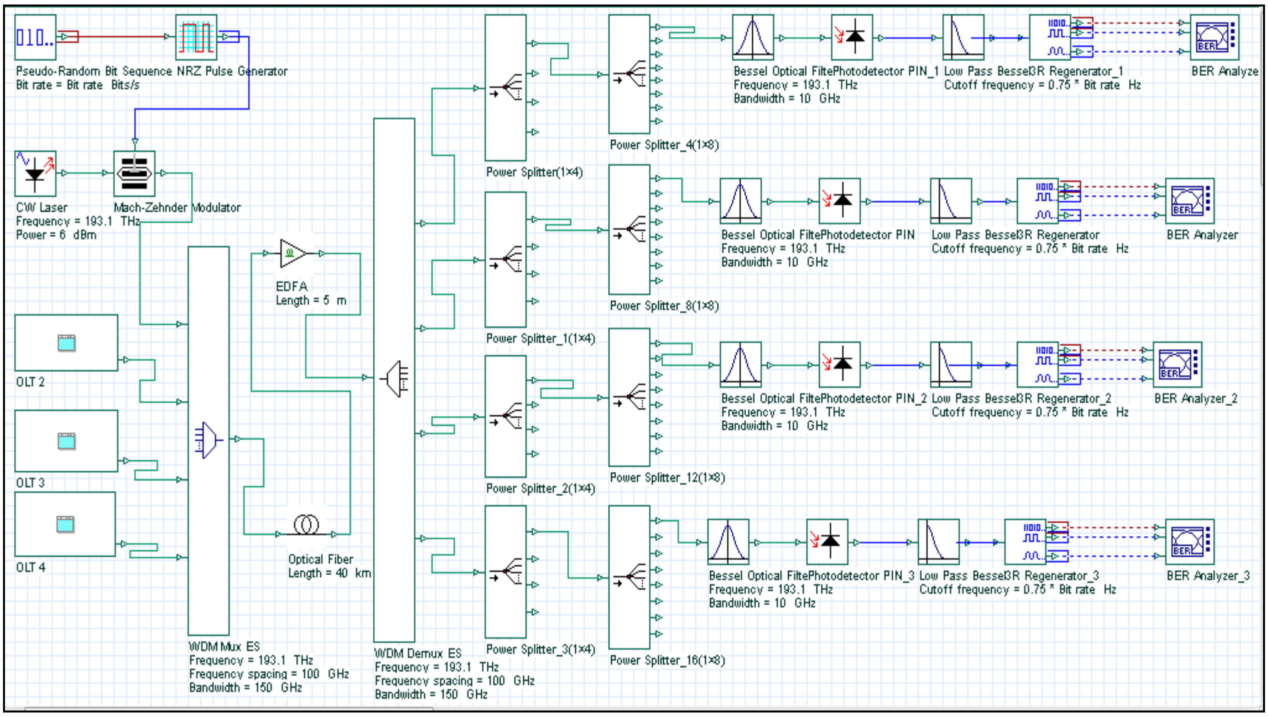


Figure IV.52 Hybrid WDM/TDM PON simulation setup (128 users)

IV.6.9 Factor influing WDM,TDM and Hybrid WDM/TDM-PONs performances(128 users)

IV.6.9.1. Impact of CW laser power

The first scenario focuses on a maximum power of CW laser, when the data rate (D) is set at 2,5Gbps, for a link length of 60km and 128 users. The simulated Q-factors and BER with different powers (P), and transmitted powers varying in the range (–6,12) dBm. Then, the results are shown in the following (Fig IV.53).

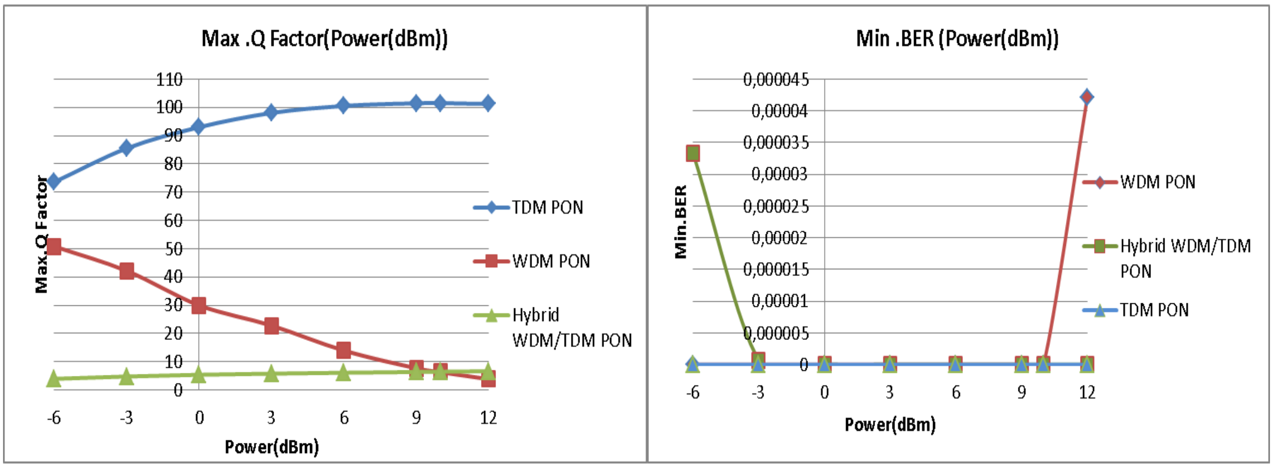


Figure IV.53 Q - Factor and Min BER versus Power for WDM,TDM and Hybrid WDM/TDM

From this (Fig IV.53) we can notice that when the power increases from -6dBm to 12dBm,Q factor increases and BER decreases for TDM PON , but for WDM PON Q factor decreases and BER increases when the power increases from -6dBm to 10dBm (for P=10dBm Q=6.43 and for P=12dBm Q= 3,87) , note that P should be less than 10dBm to guarantee BER less than 10^{-9} and Q great than 6.For Hybrid WDM/TDM PON when the power increases from 6dBm to 12dBm, Q factor increases and BER decreases (for P=-6dBm ,Q=3.98 and for P=6dBm Q=6.15), note that P should be greater than 6dBm to guarantee BER less than 10^{-9} and Q great than 6.

The comparison between WDM PON and hybrid WDM/TDM PONs justifies that the WDM PON is more advantageous than the Hybrid WDM/TDM PON especially for the low Power of CW laser.

For large input powers (in WDM), degradation of the Q factor and BER performance due to nonlinear effects such as chromatic dispersion power penalty increase[50]. For Hybrid WDM/TDM PON the Q-factor increases with an increase in input power [93].Figs IV.54 (a) ,(b),(c) and (d) show the results of eye diagrams of downlink when P is -6dBm and 12dBm for WDM PON and Hybrid WDM/TDM PON , respectively. The slope of bevel edge of eye diagram represents the sensitivity to time error of system.

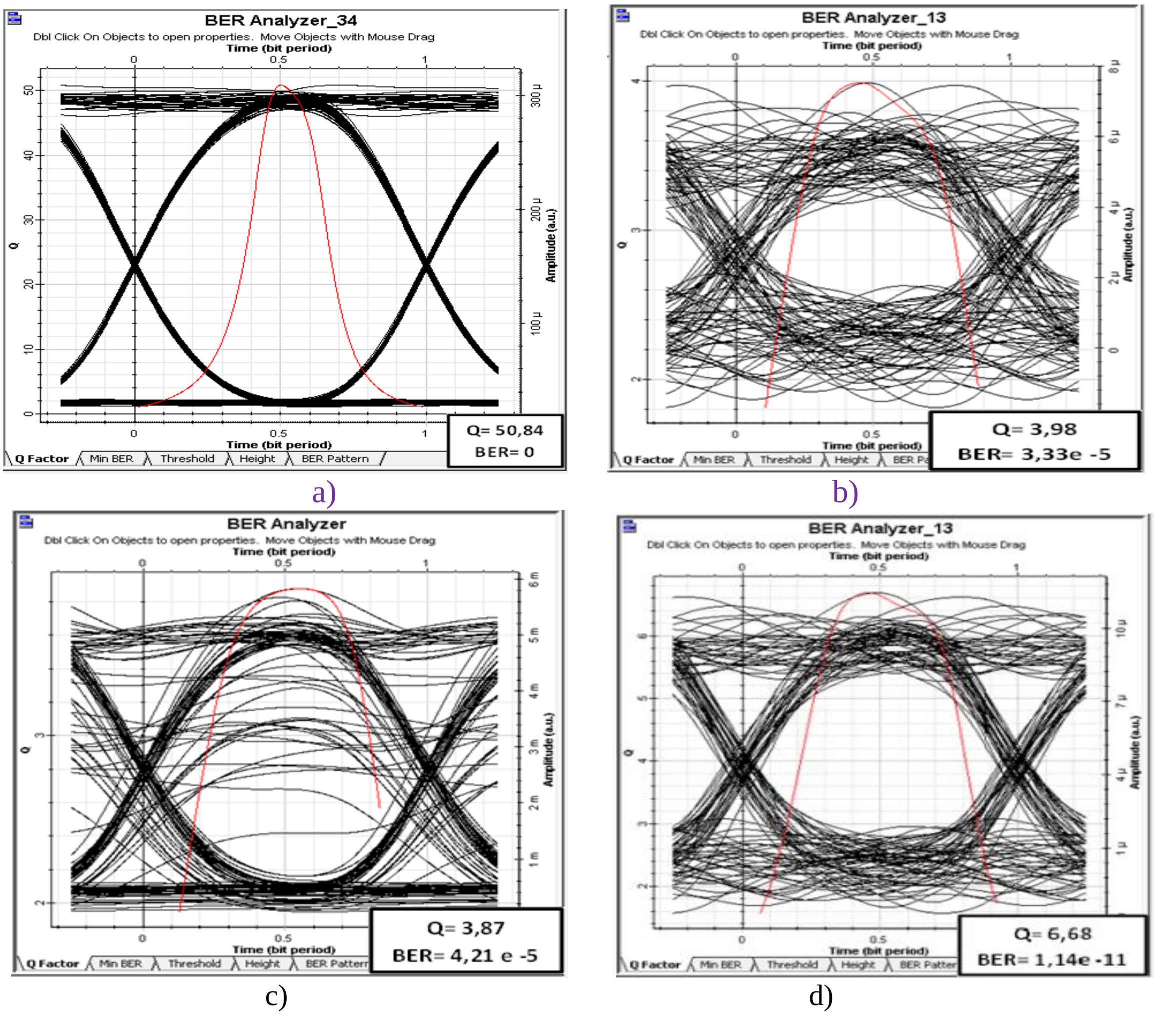


Figure IV.54 Eye diagram of downlink shown in BER analyzer, (*a*, *b*) above and (*c*, *d*) below, where the red curve represents Q-factor: *a*) WDM-PON(–6dBm), *b*) hybrid WDM/TDM-PON (–6dBm), *c*) WDM-PON (12dBm), *d*) Hybrid WDM/TDM-PON (12dBm).

IV.6.9.2. Impact of transmission distances

The second scenario investigates the maximum of fiber length allowed, when the power of CW laser is fixed at 6 dBm, a users number of 128, D about 2,5Gbps, and transmitter/receiver fibers of lengths varying in the range (5 to 240) Km.

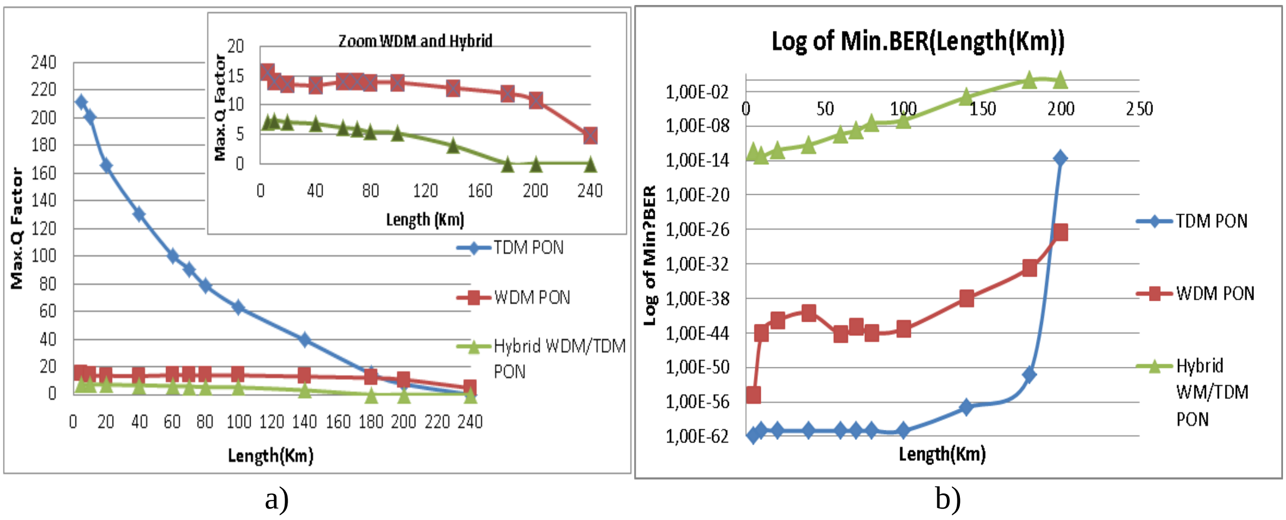


Figure IV.55 a)Q-factor and b)Log of Min BER versus (*vs*) fiber length (in Km) for WDM,TDM and Hybrid WDM/TDM

Fig IV.56 (*a*, *b* and *c*) show how eye diagrams of downlink change with a fiber length of 200km, however, Q-factor and BER results (Fig IV.55) show that Q-factor decrease and BER increase when the fiber length increases.

Q-factor and BER are respectively (7.58, 1.66E-14) and (10.71, 3.43E-27), for a fiber length (L) of 200Km, for TDM-PONs and WDM-PONs. For Hybrid WDM/ TDM-PONs and L of 200Km, Q=0 and BER=1, but L is optimized to be 60Km for hybrid WDM/TDM-PONs and 200 Km for TDM-PONs and WDM-PONs (for 128 users). (Fig IV.55) show the results of eye diagrams of downlink when L is 200Km for WDM-PONs, Hybrid WDM/TDM-PONs and TDM-PONs.

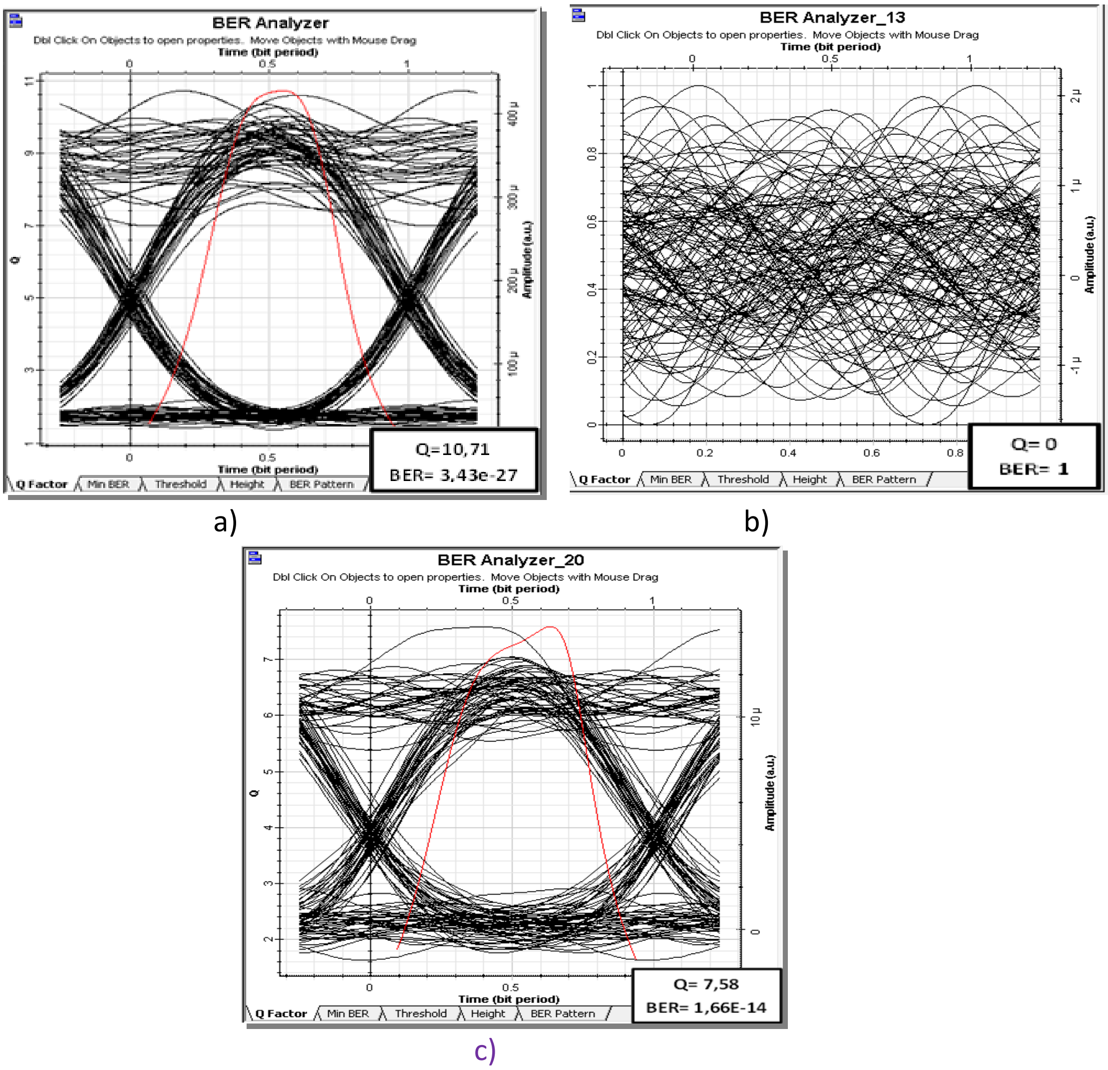
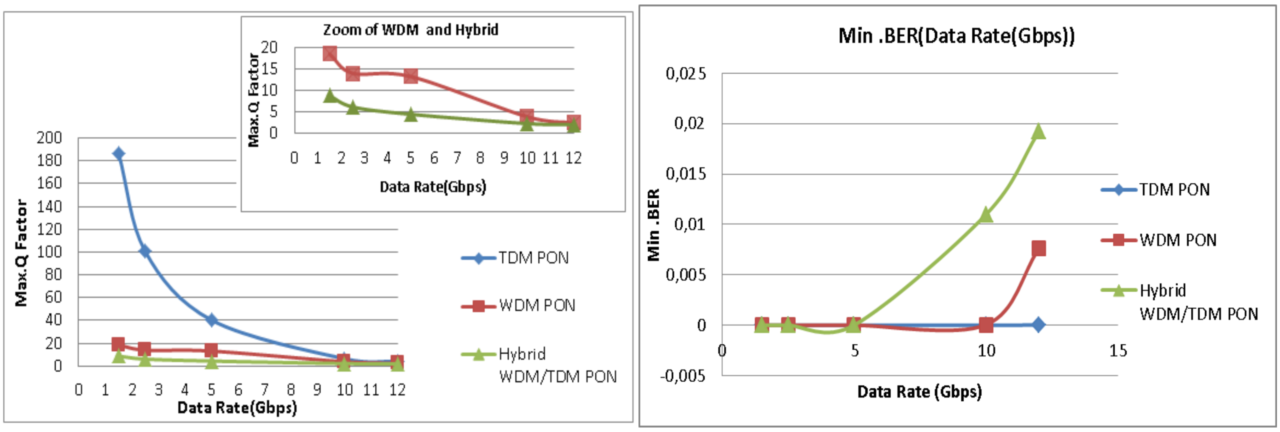


Figure IV.56 Eye diagram of downlink (for L=200Km, focusing on Q-factor again in red curve and BER value: above *a*) WDM-PON, *b* above) Hybrid WDM/TDM-PON, and below *c*) TDM-PON.

IV.6.9.3. Impact of data rate

The third scenario focuses on the max-value of the data rate, varied from 1,5 to 12Gbps. The simulated performances (quality of service) in terms of Q-factor and BER, with power CW laser and a link length fixed respectively at 6dBm and 60km, a users number of 128, are shown in (Fig IV.57).



a) b)

Figure IV .57. a)Max Q-factor and b)Min BER versus Data Rate for WDM,TDM and Hybrid WDM/TDM

It is clear from these of figures (IV.57) that Q-factor decreases and BER increases when data rate increases, and that for TDM-PON, Q is of 6,51, while BER is found to be 3,27E-11 when the data rate is D= 10Gbps. Also, for WDM-PON, Q reaches 13,24, while BER is of 2,04E-40, when D=5Gbps. For hybrid WDM/TDM PON at 2,5Gbps, Q and BER are respectively equal to 6,15 and 3,64E-10. For 128 users, D is highest for hybrid WDM/TDM-PON of 2,5 Gbps. For WDM-PONs the high data rate is 5Gbps and for TDM-PON is 10Gbps.An advantage of WDM PON is that even though users share a single fiber as well, each user as well, each user has its own channel. In the conventional PON case, the total transmission rate is divided between end users, whereas each wavelength channel has its own transmission rate with the WDM-PON networks.

IV.6.9.4. Impact of number of users

The fourth scenario studies the maximum of number of users. We have considered the data rate of the three systems, so that D, L and P are respectively 2,5Gbps, 60Km and 6dBm, We have changed many parameters such as the users number on the receiver side of the networks. Then, we obtained the results are shown in (Fig IV .58). It can be clearly mentioned that Q-factors of WDM/TDM-PON and hybrid WDM/TDM-PON decrease with the users number increasing.

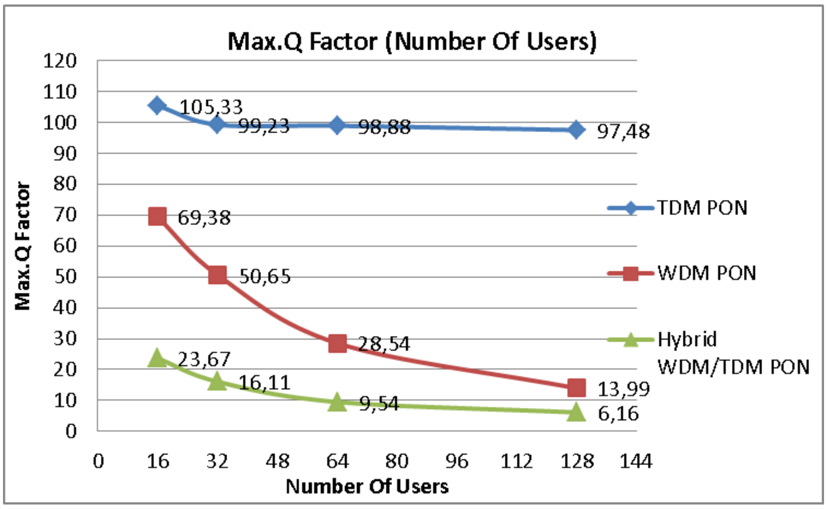


Figure IV.58 Q-factor *vs* users number for WDM,TDM and Hybrid WDM/TDM

Table IV.2. Simulation results: We collected all simulation results in Table 2 below.

N° Of Users	PON	Data Rate (Gbps)	CW laser Power (dBm)	Length Fiber (Km)	Q Factor	BER
16	TDM PON	8	0	100	7,17	3,45E-013
	WDM PON	8	0	70	6,11	4,58E-010
	Hybrid WDM/TDM	8	0	95	6,18	3,02E-010
32	TDM PON	8	0	100	6,98	1,38E-012
	WDM PON	8	3	70	6,64	1,41E-011
	Hybrid WDM/TDM	8	3	70	6,70	1,00E-011
64	TDM PON	8	3	100	7,09	5,98E-013
	WDM PON	8	6	50	7,04	8,88E-013
	Hybrid WDM/TDM	5	3	60	6,94	1,89E-012
128	TDM PON	10	6	60	6,51	3,27E-011
	WDM PON	2,5	6	60	13,99	6,66E-045
	Hybrid WDM/TDM	2,5	6	60	6,15	3,64E-010

IV.7 Performance Analysis Of WDM PON Systems Using PIN And APD Photodiodes

In this part we study the quality(Q) factor used by the receivers of APD and PIN photodiodes in wavelength division multiplexing (WDM) system with 32 number of users and compare the efficiency of the bit-error-rate(BER).The research is conducted using avalanche photo diode (APD) P-Insulator-N and PIN photodiodes receivers of different wavelengths. Interpretation and description of the Optisystem's simulation results through the optical high debit communication system, optical fiber of different lengths, bit rate , continuous wave(cw) laser power and number of users, chosen to evaluate the APD and PIN photodiodes performances in function of Q factor and BER in order to provide new perspectives for the future transmission . The simulation values show that the performance of the APD diode and the Q and BER factor obtained from APD is better than the performance of the PIN that could be expected because APD is more sensitive than PIN [47].In this part, an investigation has been done on two different photodiodes PIN and APD for use as a receiver in WDM system. It is worth queuing this work by a brief history about photodiodes in optical communication system (taken from Zeping Zhao,2017[94]).

IV.7.1 WDM PON System

PON is a network that modulates the optical wave from the optical line terminal (OLT) located at the central office (CO) and transmits it via fiber to ONUs located at the end user, designed to provide the customer with virtually unlimited bandwidths. Fiber-to - the-curb (FTTC), fiber-to - the-building (FTTB), or fiber-to - the-home (FTTH) can be described as the system [8])

WDM PON is the optimal solution for PON systems of the next –generation, the use of WDM in access networks was introduced in the late 1980s, wavelength channel spaced 100GHz (0,8nm) apart in a WDM PON. A channel spacing of 50GHz or less is used in systems known as dense WDM-PON (DWDM) .While a WDM PON does have a physical P2MP topology, logical P2P relations between the CO (central office)and each ONU (optical network unit)are facilitated[8,6])WDM PONs have been thoroughly researched as a possible technology, this PON uses multiple wavelengths in a single fiber to multiply the power without increasing the data rate.The PON architecture consiste of a single-mode fiber connecting a central connecting a central office to a multiplexer and demultiplexer network distribution facility[50].

WDM PONs, one of the most commonly used technologies for high-capacity optical communications systems, vehicle optical communications with good data transmission rates and broad bandwidths. Each communication channel is allocated to different wavelengths that are multiplexed to a single fibre by a multiplexer. At target, these wavelengths are then demultiplexed at destination by a demultiplexer and spatially separated to different receiver channels [49,50,63]).

IV.7. 2. How to design EDFA involved in WDM systems?

To determinate signal spectra, power levels, eye diagrams and its related parameters, several tools Optisystem could software offer us, OptiSystem has been studied by Optiwave to meet academic needs of system designers, optical communication engineers and researchers such as eye opening, BER and Q-factor. Fig IV.59 below, shown the schematic design of EDFA involved in the WDM system. It consists of 32 users where components and functionalities characterize the block as seen in Fig IV.59.

A/ Transmitter section

The block has the task of transmitting and modulating a continuous optical signal according to the binary data and the format chosen. the transmitter includes the following components:

- Continuous wave (CW) laser: an electroluminescent diode is used for broadband light source, whereas in CW lasers fields are intelligible momentarily.
- User Defined Bit Sequence Generator: To Generate the sequence of data bits to be transmitted.
- NRZ Pulse Generator: Pulse generator without zero return.
- Mach-Zehnder Modulator that control the optical wave amplitude, and burn the informative signal (electrical) on the light signal (Laser).

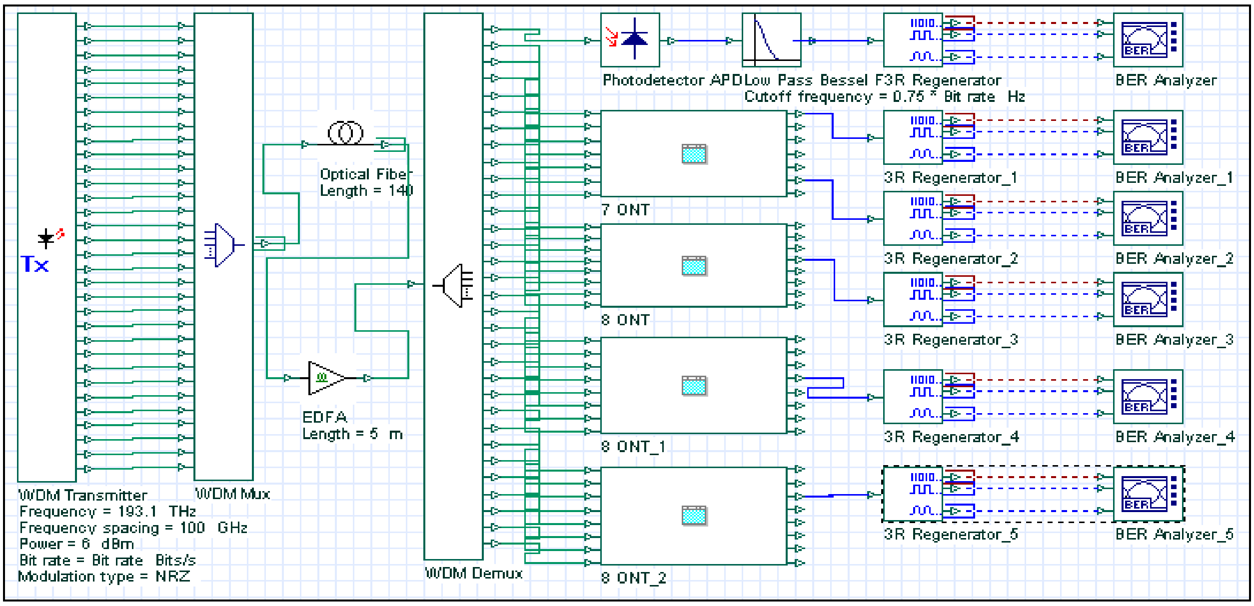


Figure IV.59 WDM PON simulation setup (32 users)

To study the Q-factor and BER of WDM PON, input-data related to WDM-transmitter are chosen such as:

- Input power 6 dBm.Frequency 193,1THz.Modulation Type :NRZ.Frequency spacing : 100GHz

B/ Channel section

Optical Fiber that represents the propagation medium of light (data) between OLT and ONT.

C/ Reciver section

Designing receivers is to receive desired efficient signals with a minimum BER, to achieve the customer's requirement. Such design comprises of:

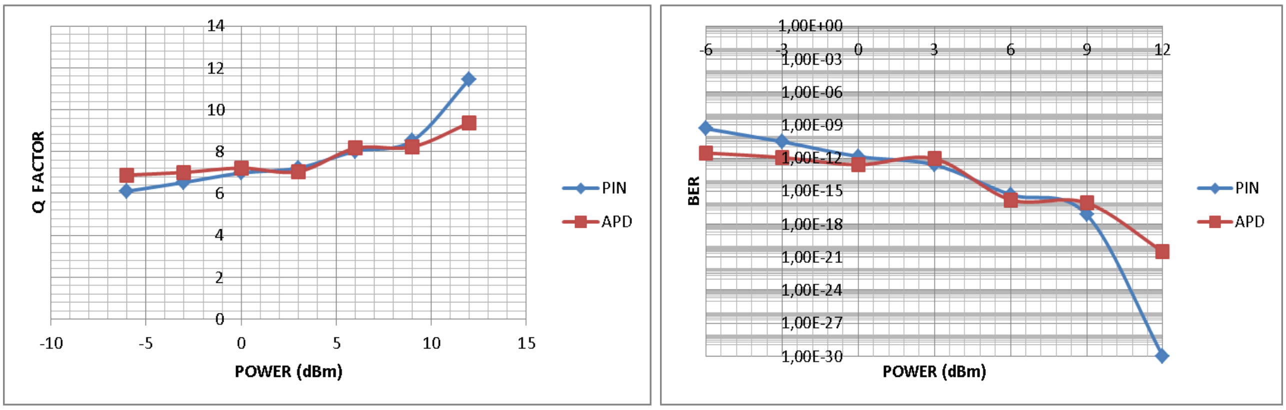
- PIN Photodetectors that detect optical signals and convert them into electrical signals.
- Low Pass Bessel Filter used to minimize the output noise of the PIN.
- 3R Regenerator making it possible to analyze/calculate the BER.BER Analyzer that displays Q-factor and BER values, and Eye Diagrams.The quality of performance of a digital communication system is specified by its BER or Q factor

IV.7.3 Factors influing the performances of WDMPON systems

Our model has analyzed the Q-factor and BER of WDM PON , using PIN and APD photodiodes with 32 users

IV.7.3.1 Impact of CW laser power

The first scenario shows a maximum CW laser power when the WDM PON data rate,D = 8 Gbps , and the fiber length is100 km. The performances are shown in (Fig IV.60) in terms of Q-factor and BER with different P values where the transmitted power varies from -6 to 12 dBm.



a) *b)*

Figure IV.60 Q-factor (a) and Log BER (b) vs Power (P)for 32 channel using PIN and APD

From (Fig IV.60), we can notice that when the power increases from –6 to 12 dBm, Q-factor increases, and BER decreases, which can be explained by the fact that P should be greater than -6 dBm to guarantee a BER less than 10^{-9} and Q greater than 6 (optical networks' requirements). And we can clearly mention that using APD is suitable for the system performance for low power(less than 0dBm). For P more than 0 dBm the photodiode PIN is convenient for the system . As for the eye diagram results, when the power is -3dBm Q equals to 7,01 for APD and 6,53 for PIN, and when the power is 12 dBm Q equals to 9,43 for APD and 11,45 for PIN ,ee below(Fig IV.61 (*a, b, c, and* *d*)à, When the eye is more relaxed it means good quality of the optical signal. The APD is better than PIN in the low power, contrary to the PIN is better than APD in the high power.

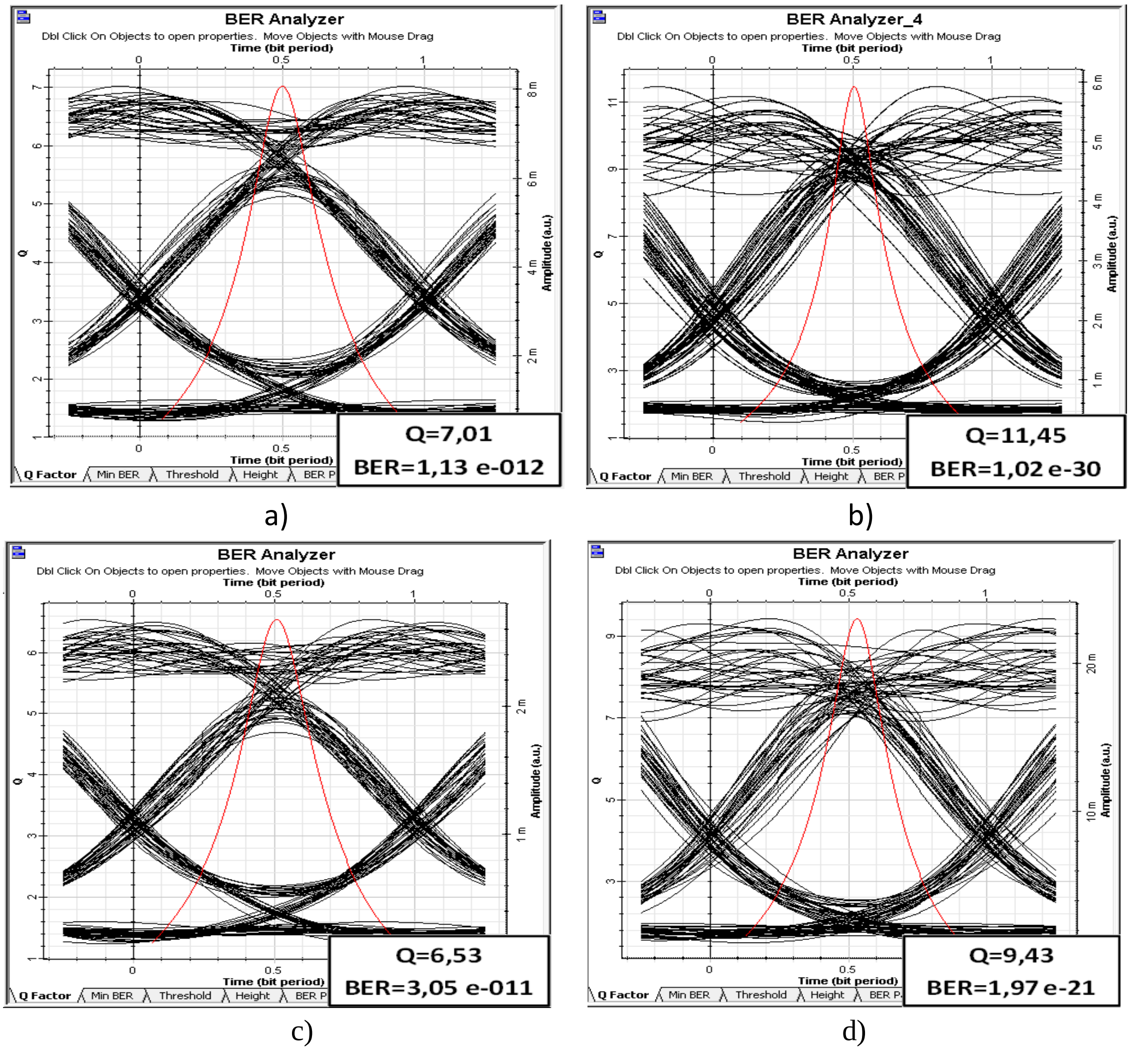
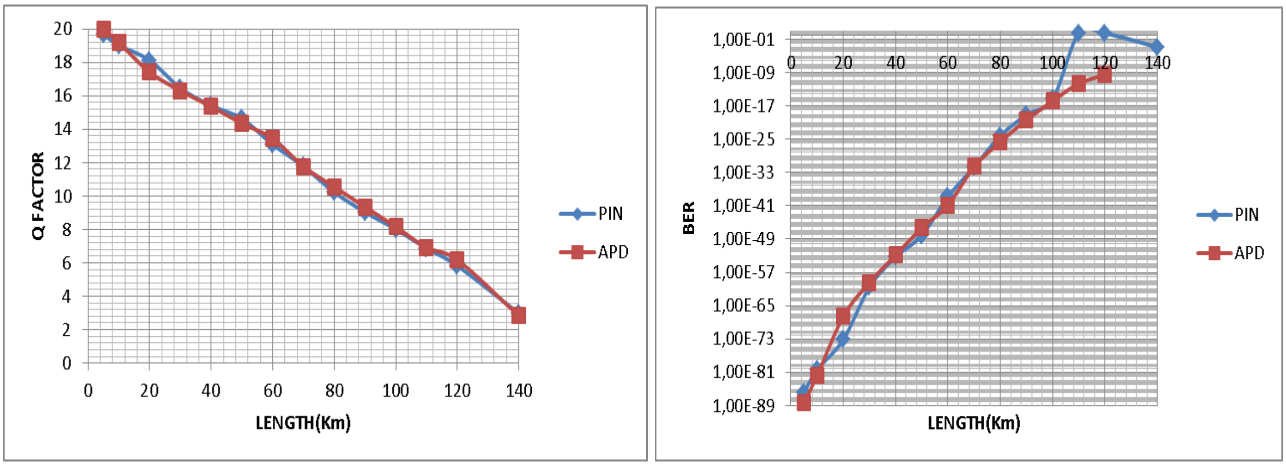


Figure IV.61 Eye diagram of downlink shown in BER analyzer for a length of 100Km, WDM PON. *a*) APD(P=-3dBm), *b*) PIN(P=-3dBm), *c*) APD(P=12 dBm), *d*) PIN(P=12 dBm).

It is the photodetection noise whose sources are generated internally in the core of the photodiode; this noise has low power but, consequently, it equivocally influences the received signal and the the transmitted information. Multiplication noise is produced specifically in APD photodiode which has an internal gain based on the multiplication method, It is only a quantum noise induced by the PIN photodiode that will be amplified by the effect of avalanche in APD photodiode, It means that the signal to noise ratio decreases with the power generated for this the PIN is better than APD in the high power.

IV.7.3.2 Impact of transmission distance

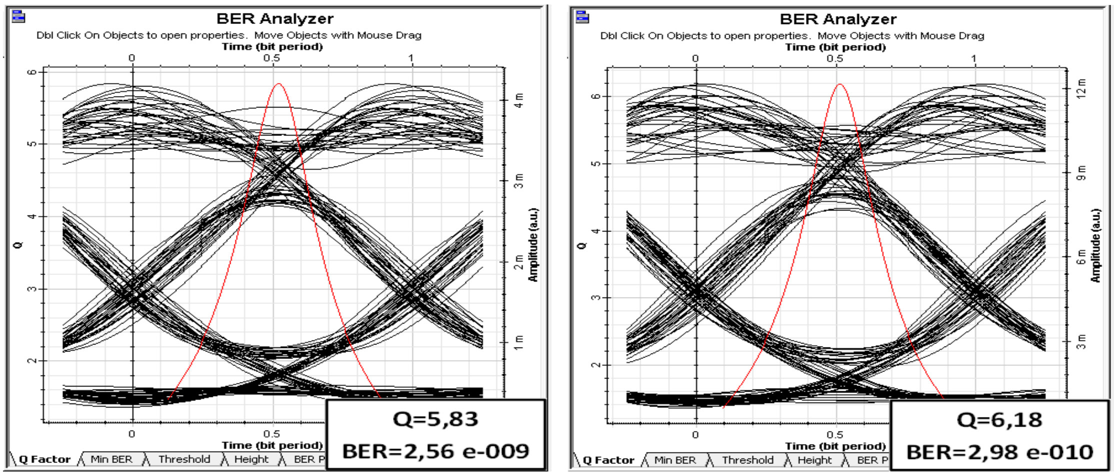
The second scenario investigate the fiber length maximum when the CW laser power number of users and D are fixed respectively at 6 dBm, 32 and 8Gbps. The fiber length transmitter-to-receiver varies between 5 and 140Km.Fig IV.62 show how eye diagrams of downlink change with the fiber length of 120km,using PIN and APD photodiodes. The results of Q-factor and BER are shown in Fig IV.62.



a) b)

Figure IV.62. Q-factor (a) and Log BER (b) *vs* length (L) using PIN and APD

One can notice that BER increases with distance increasing, in contrary to Q-factor that decreases while (L) increases, due to the loss of fiber(attenuation). Hence, a fiber length of 110Km is suitable to be chosen as an optimum length for the system using PIN, because at 110 Km the system gave a Q-factor value of 6.87 and a BER about 2.98 $\exp^{-12}$ (Q=6,91 using APD),and a fiber length of 120Km is suitable for the system using APD with Q=6,18 and BER= 2,98 $\exp^{-10}$ (Q= 5,83 using PIN) to satisfy the requirements of BER $<10^{-9}$ and Q>6.Figs(IV. 62 and 63) show that using PIN is better for the system performance for length up to 50Km, where the red curve represents Q-Factor.
so for lengths beyond 50Km, the APD is more convenient for the system. APD is better than PIN for long distances.



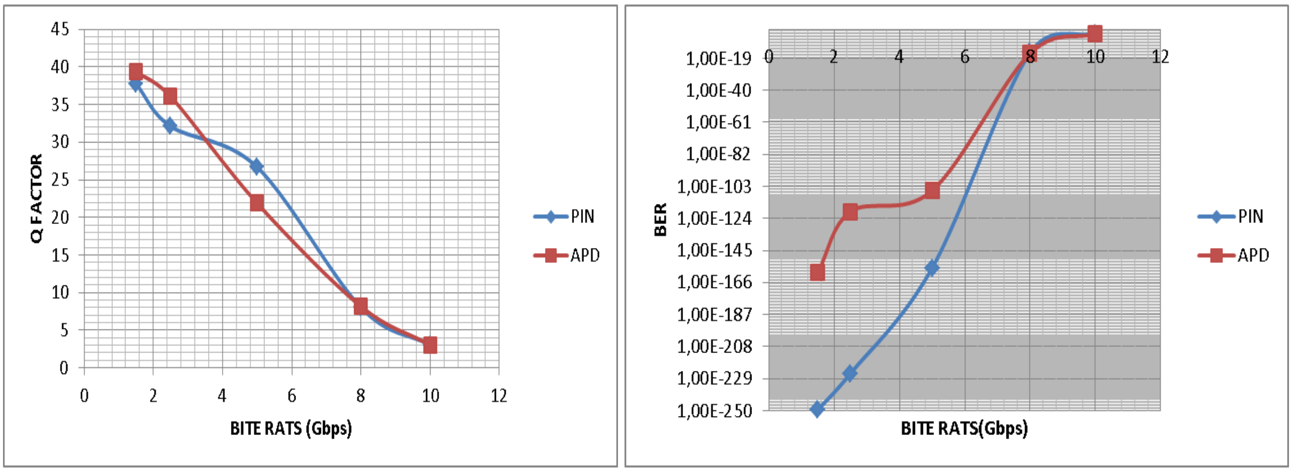
a) b)

Figure IV.63 Eye diagrams of downlink shown in BER analyzer: for L= 120 Km. a) using PIN, b) using APD.

It is the photodetection noise whose sources are generated internally in the core of the photodiode, this noise has low power but, consequently, it equivocally influences the received signal and the transmitted information. Multiplication noise is produced specifically in APD photodiode which has an internal gain based on the multiplication method, It is only a quantum noise induced by the PIN photodiode that will be amplified by the effect of avalanche in APD photodiode, It means that the signal –to - noise ratio decreases with the power generated for this the PIN is better than APD in the high power.

IV.7.3.3 Impact of Data Rate

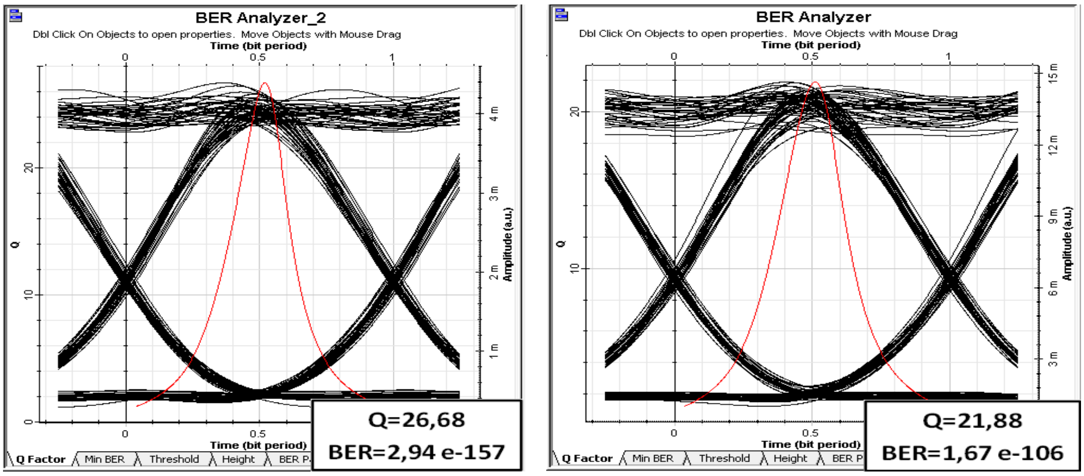
To evaluate the impact of data rate transmitter-to-receiver, this is varied between 1,5 Gbps to 10Gbps. The performances in terms of both Q-factors and BER simulated with power CW laser at 6 dBm for a link length of 100 km and users' number of 32 are shown in (FigsIV.64 and 65).



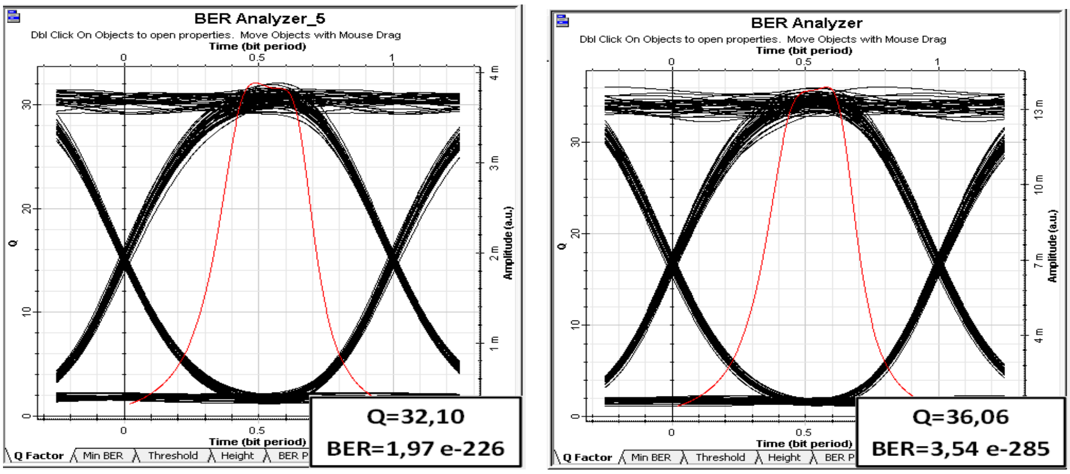
a) b)

Figure.IV.64 Q-factor a) and Log BER b) vs Bite rats using PIN and APD

The BER and Q factor are shown in (Fig.IV.64), where we can notice that BER increases and Q-factor decreases (i.e. performance degrades) when the bit rate increases. Such performance degradation is explained by the increase of the interferences between the data bits in the channel. This leads to poorly detect the bits of receiver. Such result can be concluded as high data rate will give a lower Q-factor.This states that the greater the input debit increases the noise of the photodetection but the observed signal is fairly attenuated APD shows a better performance compared to PIN at a low bit rate (less than 2.5 Gbps) . But the output in APD is reduced at a higher bit rate (more than 2.5 Gbps), and becomes outstanding in PINThe APD is better than PIN in the low bite rats, in contrary the PIN is better than APD in the high bite rats.(Fig.IV.64) show the eye diagrams of downlink when D (data rate) is 5 Gbps and 2,5 Gbps, respectively.



a) b)

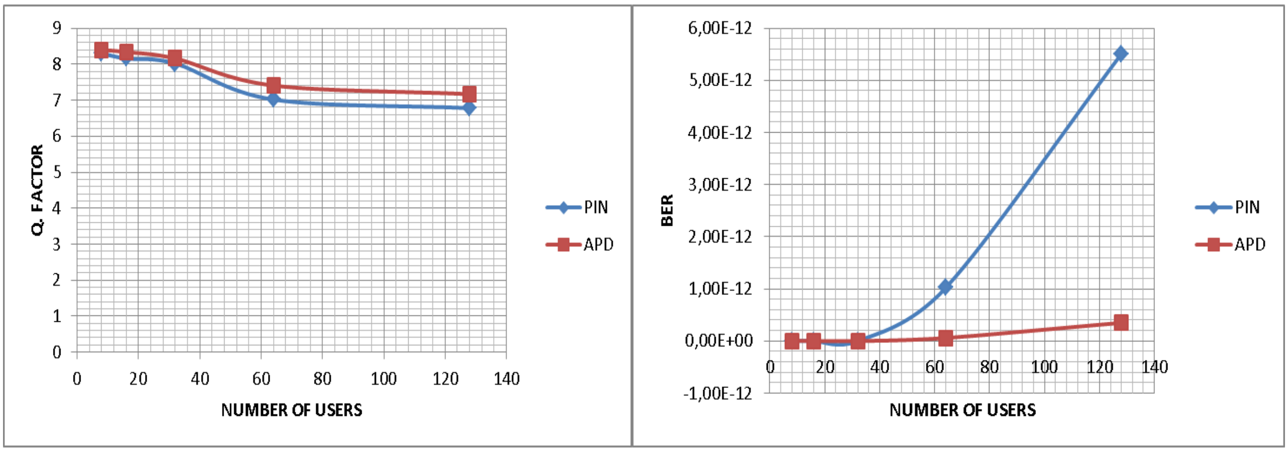


c) d)

Figure IV.65 Eye diagrams of downlink shown in BER analyzer, where the red curve represents Q-factor: *a*) PIN (D = 5Gbps), *b*) APD(D =5 Gbps), c) PIN(D = 2,5Gbps),d) APD(D =2,5 Gbps)

IV.7.3.4. Impact of number of users

We considered the data rate of the WDM PON system, with D of 8Gbps, a distance of 100 Km, and a power of 6dBm, by changing the parameters such as the users' number in the receiver side of the network, to we get more results. One can mention that the system performances (as shown in Fig IV.66)) were more deteriorated due to the fact that the increase the interference between the data bits, which leads to bad data detection. As a result, when the number of active users increases, the interference increases, and the performances of the system deteriorate more.



a) *b*)

Figure IV.66 Q-factor(a) and BER(b) *vs* users' number using PIN and APD

One can clearly mention that using APD is better for the system performance, and Q-factor performance of APD is higher than that of PIN. Comparing PIN with APD photodiodes reveals that the APD is more advantageous than the PIN photodiode for the high number of users. and by using APD in the receiver the number of active users increased.

The main difference between using APDs vs. PIN diodes is that while PIN diodes work based on the device's responsivity, APDs can actually generate a gain in the signal.This gain will increase the bandwidth of the Optical Fiber Multiplexing and Emerging Techniques receiver architecture which results in a higher data rate for the device[95].

IV.8 Conclusion

Optical local area network (LAN)system gives a successful answer for future access systems on account of its gigantic data transmission and vitality investment funds, we planned optical LAN at high speed a single fiber shared between multiple users. we studied the performance of an optical LAN transmission system by simulations by analyzing the impact of optical power, transmission distance, data rate, and number of users.

Passive Optical Networks (PON) plays an important role in the development of the Fiber to the home (FTTH) networks. The PON is considered as one of the most successful access architecture that can provide high capacity and long reach, in a summary, different modulation techniques are used for upgrading optical wireless communication systems, the system performance has been investigated using NRZ and RZ formats, by analysing the optical power impact , transmission distance, data rate and number of users,the analysis has shown that RZ modulation forma is excellent in comparison with conventional NRZ modulation format for the short distance and for low bit rate (RZ is so good in performance compared to NRZ especially for D=2,5Gbps) according to the optical network rrequirements (Q>6 and BER<10-9),also, it gives excellent performance for a low power of CW laser in short distances, , also we conclude that RZ works in short distances, and it is better in law bit rate, this means we can increase the distance in the system using RZ with law bit rate (for ex 1,5 Gbps and 2,5Gbps).

For future optical communication, low cost, light weight and highly sensitive integrated optical receivers are needed. Our simulations is to study a WDM system performances using two types of photodiode: PIN and APD, this research also aimed at characterizing these photodetectors by examining their performance in terms of different functional parameters by measuring the BER and Q factor, which is a very important factor in determining the quality of optical detection for the high-debit optical communication. The comparison between the PIN and APD photodiodes warrants that the APD photodiode is more advantageous than the low-power PIN photodiode , while the PIN photodiode is always more efficient for high-power photodiodes above 10dBm it means that the signal-to-noise ratio decreases with the power generated, and we found APD offering better performance over PIN at a low bit rate however, the Q-factor value is maximum when using APD as the receiving photodiode , and minimum when using PIN diode as the receiving photodiode for the low bite rats (less than 2.5 Gbps) , in contrary the PIN is better than APD in the high bite rats, the result shows that the APD receiver is suitable to be used to accommodate higher number of users with lower bit rate . Performance of GPONs system using different modulation techniques such as NRZ, RZ has been analyzed by Optisystem software with PINs and APDs reveals a great preference proviede by using EDFA. It can be concluded that EDFA could be used to compensate the optical signal loss in order to increase the transmission length.

Motivated by the fact that PONs play a key role in developing FTTH networks, we have evaluated their performances using the simulation tool, exploiting OptiSystem software, where TDM- WDM-PONs and hybrid WDM/TDM-PONs (access networks architecture) were successfully designed using 16 and 128 users, and evaluated in this research work. Eye-diagrams, Q-factors and BER are shown to evaluate the performance of proposed systems at different situations, an analysis has been done, from which it can be seen that for the same data rates, the performance of the unidirectional TDM PON is better (but via sending the same frequency for multiple subscribers) ,the comparison between WDM-PONs and hybrid WDM/TDM-PONs justifies that WDM-PONs are more advantageous and much convenient than hybrid WDM/TDM-PONs, especially for low powers of CW lasers, it is worth noting that P should be less than 10dBm for WDM and greater than 6dBm for hybrid, to guarantee BER less than 10^{-9} and Q-factor beyond 6. Multiplexing the time division (TDM) is a technique in which multiple subscribers in the time domain share the same frequency, while for WDM separate optical sources for various channels increase both system complexity and network costs ,and therefore hybrid WDM/TDM multiplexing is seen as the strategy for PON-based access networks of the next-generation , and we used just four frequencies to reach 128 subscribers, making them useful in bandwidth intensive and cost effective .

These simulations are first approaches that allow us to verify and determine the parameters in order to install the optical communication system according to the optical network requirements ($q>6$ and $ber<10^{-9}$).

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General Conclusion and Perspectives

The rapid development of fiber optic communication systems requires higher transmission data rate and longer reach. This work was initiated following the rapid growth of optical networks, and the need to have devices in the devices in the network that can allow the exploitation of the performances offered by theoptical fiber, namely its bandwidth and speed.

After a state of the art made on various technologies of implementation of the optical fiber , we fixed the objective of this work, which consists in the exploitation of several technologies used in networks. We have focused on designing networks and planning problems of long distance optical networks, on the basis of Time Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM) and Hybrid WDM/TDM systems, and shown impacts of several parameters on the transmission quality, with different users via varying fiber lengths, data rates, wave laser powers, by using PIN/APD detectors and RZ/NRZ modulations. Performances of such systems have been analyzed basing on Q-factors, BERs, and eye diagrams using Optisystem.

The **first chapter** focuses on the role of optical fibers as communication channels in light wave systems. An important part has been dedicated to the fundamentals physics phenomena describing optical propagation in optic fiber channels. First, we have described how the light is transmitted through optical fibers, and given details on their working principles, by discussing various optical effects that occur when light is transmitted through such transmission channels. In optical transport networks of telecoms, increased transmission rates and/or distance are partly responsible for the performance degradation of an optical network transmission.

Chapter II presents a literature review of channel multiplexing techniques, explains fiber-to-the-home (FTTH) transmission, introduces the structure of optical networks with a particular interest for passive optical network (PONs) and their evolution, and describes Frequency/Time Division Multiplexing (FDM/TDM), plesiochronous transmission hierarchy (PDH), plesiochronous digital hierarchy, synchronous digital hierarchy (SDH) and SONET (synchronousoptical network), on which we have detailed channel multiplexing techniques and basic principles, and explained TDM ,WDM, CDMA and OFDM-based systems. It was shown that fiber losses inevitably limit the transmission distance of our optical fiber communication systems; optical amplifiers were used by long-haul fiber-optic communication systems to compensate fiber losses.

In **Chapter III**, we have explored the three optical amplifiers technologies for optical telecoms: EDFA, Raman and SOAs. We first started with describing EDFA (made up of a small length of fiber, doped with Erbium, and is pumped by high-power lasers), generally regarded as one of the most significant optical amplifiers in distributed optical fiber sensors, able to mitigate losses of

the optical power. EDFA bandwidth is usually the whole C band (1530 to 1565 nm), however Fiber Raman amplifiers take use of the stimulated Raman scattering phenomenon in fiber by pumping it 14 THz above the required gain frequency. We concluded that Raman amplifiers use transmission fiber as the gain medium, distributing the total gain throughout the length of the fiber. The gain produced by the pump laser can perfectly equal the loss imposed by the fiber medium for properly adjusted pump power, maintaining signals constant as average powers along fibers, then SOAs can be used in both nonlinear and linear modes of operation. Compared to Raman and EDFA amplifiers, SOAs are the best options due to compact size and low power compensation they own.

In the **last chapter**, results throughout published works have been discussed. After modeling optical channels and optoelectronic components with realistic parameters, a performance evaluation of NRZ modulation was validated, to meet the ever increasing bandwidth needs of users, FTTH and systems with more than 10 Gb/s PON are expected to be introduced. Speeds of up to 40 Gb/s over ~ 60 km or more are expected, with sharing rates of at least 64 users, without modifying the basic infrastructure: modulation formats with better spectral efficiency than NRZ can be used.

We have shown that RZ modulation is excellent compared to conventional NRZ format for short distances and low bit rates, mainly for 2,5Gbps according to PONs requirements (Q>6; BER<10-9); It gives excellent performance for low powers of CW laser in short distances. For an input power of 20 dBm, systems perform best by using RZ modulation for short distances, and are suitable for 20 dBm input powers with NRZ for long distances.

On another hand, we performed WDM systems by using both types of photodiode: PIN and APD, and found that APD is more advantageous than low-power PIN photodiode, while PIN is more efficient for high-power above 10dBm, and APD can offer better performance over PIN at low bit rates. However, Q-factors are maximum when using APD, and minimum while exploiting PIN for low bite rats (<2.5 Gbps). In contrary, PIN is much better than APD for high bite rates. Also, we have evaluated the performances of PONs, exploiting OptiSystem software, where TDM-, WDM- and hybrid WDM/TDM-PONs were successfully designed using 16 and 128 users, and found that hybrid WDM/TDM multiplexing is a convenient strategy for PONs of the next-generation, where four frequencies have to be taken into account to reach 128 subscribers by mixing WDM and TDM.

As a next future work, we intend to experimentally test the above developed/simulated techniques on a real test bench, to accurately evaluate performances and validate our simulation results. Further studies, based on these realistic optical channel models, are interesting to be carried out by studying the dispersion compensation fiber (DCF), and the compensation with Fiber Bragg Grating (FBG)