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Performance Analysis of AWG Based TWDM-PON using FBG and Optical Amplifiers.

Friehiwot, Zelalem

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By

Friehiwot Zelalem

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

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Performance Analysis and Evaluation of AWG Based TWDM-PON using FBG and Optical Amplifiers.

By

Friehiwot Zelalem

Advisor: Prof. Pushparagavan A

Declaration

This is to certify that the thesis entitled " Performance Analysis and Evaluation of AWG Based TWDM-PON using FBG and Optical Amplifiers ", submitted in partial fulfillment for the degree of Master of Science in Communication System Engineering under the faculty of Electrical and Computer Engineering, Bahir Dar Institute of Technology, is a record of original work carried out by me and has not been submitted to this or any other institution to get any other degree or certificates. The assistance and help I received during the course of this investigation have been duly acknowledged.

Friehiwot Zelalem	[signature]	29/12/2015 E.C
Name of the candidate	Signature	Date

This thesis has been submitted for examination with my approval as a university advisor.

Prof.Pushparaghavan Annamalai	[signature]	04/09/2023 GC
Name of the candidate	Signature	Date

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Thesis Approval

I hereby confirm that the changes required by the examiners have been carried out and incorporate in the final thesis.

Name of Student Friehiwot Zelalem Signature ______ Date 29/12/2015 E.C

As members of the board examiners, we examined this thesis entitled "Performance Analysis and Evaluation of AWG Based TWDM-PON using FBG and Optical Amplifiers". We hereby certify that this thesis is accepted for fulfilling of the requirements for the award of the Degree of Master of Science in Communication Systems Engineering.

Board of Examiners

	Signature	Date
Name of Advisor Prof. [illegible]	Signature	Date 04/09/2023 G.C
Name of External Examiner Dr. Zelalem Hailu	Signature	Date 27/08/2023
Name of Internal Examiner Dr. AMARE KASSAW.	Signature	Date 29-12-2015 E.C
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Abstract

The design of cost effective Optical Line Terminal (OLT) for TWDM-PON based arrayed waveguide grating (AWG) is designed. However, while providing high data rate and longer transmission distance, TWDM-PON suffers from fiber dispersion and attenuation, which several limits on system performance. The performance of the different modulation formats on the proposed improved TWDMPON architecture transmission system is examined. In this thesis, TWDM-PON architecture based on Fiber Bragg Grating (FBG) and different Optical Amplifier (OA) for extended transmission distance is proposed. FBG dispersion compensation is considered in order to tackle the dispersion problem and increase transmission distance. And the optical signal needs to be amplified by using SOA, Raman and Erbium Doped Fiber Amplifier (EDFA) in order to compensate for the losses in the transmission. The performance of the proposed system is analyzed and the performance of different modulation formats is measured and analyzed in terms of BER and Q factor values. One multicarrier input from the PM which provides seven different wavelengths from 186.4 – 187.4 THz with 100 GHz frequency spacing. AWG routs each wavelength frequency of 187 THz, 187.1 THz, 187.2THz, and 187.3 THz. At 45 km single laser source TWDM-PON achieves Max Q factor of 6.119989 for 10 dBm input optical power and TWDM-PON with four laser sources gives Q factor of 6.232882 which shows relatively same performance. Duo Binary modulation format shows better performance in achieving 5.75 E-10 Min BER at 50 km transmission distance. The EDFA outperforms SOA and Raman in terms of Q factor and Min BER for fiber lengths ranging from 5 to 50 km, having a 4.50E-10 and 06.24 Min BER and Q factor value respectively, EDFA achieves 49 km. The Min BER was 6.67E-10 for EDFA and 2.02E-09 for RAMAN with best acceptable value at 100 km and the SOA Min BER value was 1.19E-08 with FBG dispersion compensation

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First and foremost, I want to express my gratitude to Almighty God for giving me the ability to do this work. I sincerely appreciate the assistance, support, and encouragement I received from Professor Pushparaghavan Annamalai as he helped me complete my thesis. He also has my sincere gratitude for pushing me to finish this work and having faith in me. Finally, I would like to thank my husband and family, whose endless support helped me to finish my thesis.

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Abbreviations

APD	Avalanche photo Detector
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
BR	Bit Rate
CD	Chromatic Dispersion
CO	Central Office
CRZ	chirped Return to Zero
CSRZ	Carrier Suppressed Return to Zero
CW	Continuous Wave
CW-LD	Continuous Wave Laser Diode Laser
DB	Duo Binary
DC	Direct Current
DCF	Dispersion Compensation Fiber
DD	Direct Detection
DEMUX	De-multiplexer
DPSK	Differential phase shift keying
DQPSK	Differential Quadrature PSK
EDFA	Erbium Doped Fiber Amplifier
EO	Electro-Optic
FGB	Fiber Bragg Grating
FPR	Free Propagation Regions
FSR	Free spectral Range
FTTX	Fiber to the “x”
IM	Intensity Modulation

IP	Internet Protocol
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
LD	Laser Diode
LPF	Low pass Filter
MAX	Maximum
MMF	Multimode Fiber
MODB	Modified Duo binary
MUX	Multiplexer
MZM	Mach-Zehnder modulator
NF	Noise Figure
NRZ	Non return to zero
NRZDPSK	Non return to zero DPSK
OA	Optical Amplifier
ODN	Optical Distribution Network
OLT	Optical Line Terminal
ONU	Optical Network Units
OSNR	Optical signal to noise ratio
OUT	Out Put
P_{ASE}	Power amplified spontaneous emission
PB	Power Budget
PM	Phase Modulator
PM	Power Margin
PMD	Polarization Mode Dispersion
PON	Passive Optical Network

PR	Power Received
PRBS	Pseudo-Random Bit Sequence
PS	Power Splitter
PSK	Phase Shift Key
PT	Power Transmitted
QPSK	Quadrature Phase Shift Key
RF	Radio frequency
ROA	Raman Optical Amplifier
RSOA	Reflective Semiconductor OA
RZ	Return to Zero
RZ-DPSK	Return to Zero DPSK
SMF	Single mode Fiber
SNR	Signal to noise ratio
SOA	Semiconductor Optical Amplifier
SRS	Stimulated Raman Scattering
TDM	Time division Multiplexing
TDMA	Time division Multiplexing Access
TNR	Good tone to noise ratio
TWDM	Time and Wave division Multiplexing
UDWDM	Ultra dense WDM
UV	Ultra Violate
WDM	Wave division Multiplexing
WDMA	Wave division Multiplexing Access
WR	Wave length Routing

Symbols

λ	Wavelength
f_s	signal with fixed frequency
f_c	CW laser frequency
E_{in}	Input field
V_d	Electrical driving voltage waveform
V_{bias}	DC bias
λ_B	Bragg wavelength
n_{eff}	Effective core refractive index
Λ	Grating period
n_0	Variation in refractive index
η	Fraction of power
n_{core}	unexposed core refractive index
δn	photo induced index change
N_0	carrier density
α_g	differential gain parameter
g_T	gain coefficient
G	total gain
n_{sp}	spontaneous emission factor

Chapter 1

Introduction

1.1 Background

In recent years, Internet traffic is growing very rapidly due to the rapid increase in bandwidth demand from the number of users with video-based interactive and multimedia services with high processing speeds such as video conferences, voice over IP, e-commerce, and interactive games. As a result, future access networks need to attain higher bandwidth for high data rate at lower cost. Optical broadband access networks have emerged in order to increase channel capacity to meet this ever-increasing demand for bandwidth access. A passive optical network (PON) which is used to provide fiber to the end consumer domestically and commercially becomes popular for its efficiency and cost-effectiveness compared to copper networks. PON have become a way to fulfill the growing demand for rapid increases in bandwidth for low-cost, high-bandwidth, and long-range access networks [1].

PON consist of three main parts, an Optical Line Terminal (OLT) at the central office which works as the transmitter, modulate the downlink data and send the data out to the fiber, Optical Network Units (ONUs) which is connected through optical fiber to the OLT and it is located close to the customer premises and Optical Distribution Network (ODN) is located between OLT and ONU in which used to connect the OLT to different ONUs by using passive optical distribution element. The PON system is built on a shared structure that enables bi-directional communication between ONUs and OLT. The downstream traffic is broadcast from the OLT to all ONUs, while the upstream traffic is transmitted from the ONUs to the OLT through one fiber [2].

Over the past few years, PON architectures have been mainly concerned by time division multiplexing (TDM) and wavelength division multiplexing (WDM) [3]. In TDM PON networks, the bandwidth is shared by multiple subscribers using a time division multiple access scheme; all the users share the same wavelength to transmit the information and it has a low installation and maintenance. In WDM PON, multiple wavelengths are used by each user using WDMA; thus, it can provide a secure service to the large number of users over a single path. The TDM-PON and

WDM-PON cannot satisfy the growing bandwidth demand since, both TDM and WDM techniques have their own advantages as well as limitations. TDM limits the bandwidth of each user. It also suffers from power splitting losses and lower data rates while WDM has inefficient bandwidth utilization and higher implementation cost than TDM-PON [4]. Therefore, to overcome the limitations of TDM and WDM PONs, hybrid WDM/TDM is one of the promising technologies. The combination of this two multiple access could be the most cost effective way to fulfill the future increasing demand.

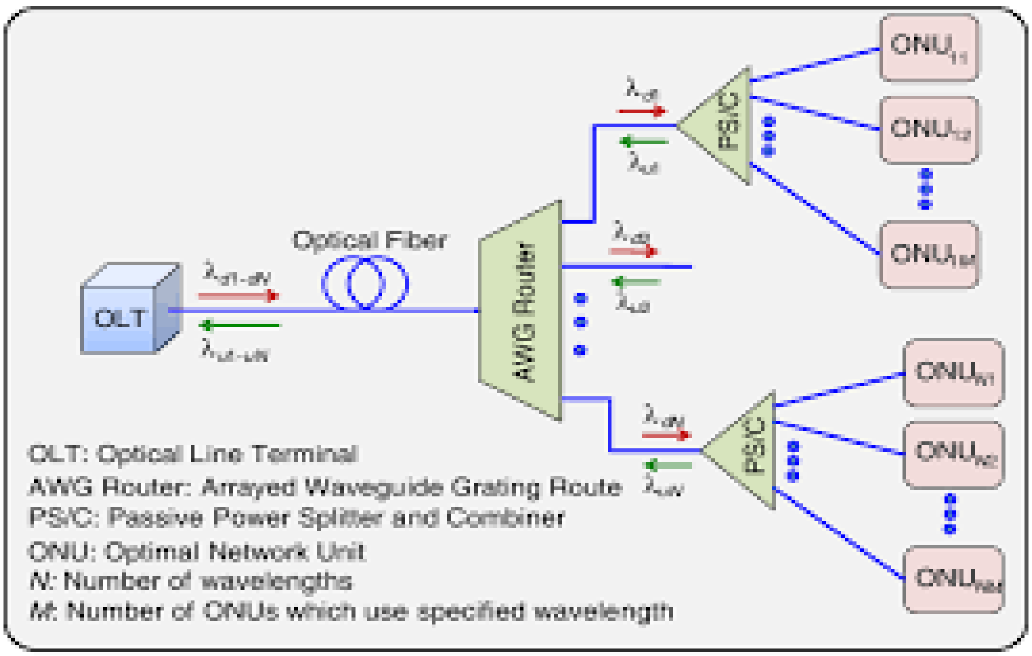

Figure 1.1 The hybrid TDM/WDM PON Network architecture [4].

1.1.1 Passive Optical Network

Recently, the last mile broadband access network has faced a problem due to the increasing rise of bandwidth-intensive applications, which calls for lower costs, greater capacity, and improved flexibility [5-6]. The bandwidth capacity of the currently used access technologies, DSL, HFC, and wireless, has somewhat increased. Therefore, to satisfy the ever-increasing bandwidth demand, service providers will need to deploy optical access networks. We are already witnessing a worldwide deployment of optical access networks and a steady increase in the number of FTTX users [7].TWDM PON is one of the most promising candidates for NG-PON2 networks due to its ability to serve a large number of subscribers and offer high capacity per user. In TWDM PON (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 [8]. TWDM PON increases the number of working wavelengths in each stream to exploit the high bandwidth of optical fibers. On the other hand, TWDM PON bridges the gap between TDM PON and pure WDM PON and can be deployed by smoothly migrating from the currently deployed TDM PON [9]. Since the existing schemes in PON are facing the problems of circuit complexity and higher costs, utilization of multi-carriers based on a single laser source for independent transmission from the OLT in a PON would be necessary. The multi-carrier's source may replace the laser array or several lasers used at OLT and may result in a cost effective OLT in TWDM PON system.

1.1.2 Optical Line Terminal (OLT) in TWDM

In WDM-PON the design architecture and the techniques used for generation of signals for upstream and downstream transmission plays a crucial role towards network efficiency [3]. The costs of TWDM-PON can be significantly reduced by employing novel cost effective optical line terminal (OLT) and colorless optical network units (ONU). In typical TWDM-PON a specific wavelength is assigned to each user. So a wavelength tunable laser is an attractive source for offering several wavelengths simultaneously in this situation. However, the tunable lasers are quite expensive in order to fulfill the requirement of the network as there would be a large number of users and the demand is increasing day by day. The coherent tunable lasers are costly due to the sophisticated technologies used in the designation of lasers, such as distributed brag grating and superstructure grating. The primary setup for the cost reduction of a PON is the designing of cost-effective OLT by employing the multi-tone frequency comb generators instead of coherent tunable laser devices [2]. In order to balance a compromise in data speed, fiber range, and power splitter ratio for a variety of applications, NG-PON2 systems need elasticity. One of the most effective PON resolutions for running high capacity bandwidth for broadband services is TWDM-PON, in which each wavelength is shared among several ONUs utilizing TDMA [10-11].

The multi-carrier's source may replace the laser array and may result in a cost effective OLT in TWDM PON system. The proposed multi-carrier's source TWDM-PON is generated in OLT is used in the downstream transmission based AWG as a wavelength routing component with four channels using 4-optical multi-carriers from a single source each channel transmits a data rate of 10-Gbps.

1.2 Statement of Problem

The rapid increase in bandwidth demand from different applications drives the need for high speed data transmission capabilities of access networks. TWDM-PON is considered to be the best trend of the next generation for meeting the requirements of internet traffic growth. In addition to Meeting huge bandwidth demand, there should be a cost-effective way to upgrade TWDM-PON capacity. However, improving the TWDM-PON capacity (high data rate and longer reach) is challenging since fiber dispersion imposes several limits on system performance. But, this causes technical challenges in achieving the required optical power budget and the decrease in dispersion tolerance. The design of OLT transmitter also need be provisioned for cost effective TWDM-PON system in order to meet standards of next generation access network. The other thing which has a major impact on system performance is the modulation format. Thus, determining the appropriate type of modulation format for a specific optical fiber transmission system has a great influence on the spectral efficiency and transmission capacity of the system. Those challenges show the importance of studying the effect of improved design of cost effective OLT on the system performance and examining the performance of dispersion compensation technique and optical amplifier in achieving high data rate and longer optical transmission distance for TWDM-PON under different modulation formats.

1.3 Objective

1.3.1 General Objective

The main objective of this research is to evaluate the performance of TWDM-PON system using the Arrayed Waveguide Grating (AWG) and different optical amplifier OA under different modulation formats.

1.3.2 Specific Objectives

- To design and implement an efficient TWDM-PON system with a low cost OLT design using AWG.

- To improve the data rate and transmission distance of TWDM-PON system based on FBG dispersion compensation and different Optical Amplifiers.
- To compare performance of SOA, RAMAN and EDFA amplifiers on the proposed AWG based OLT for TWDM-PON using FBG for dispersion compensation.
- To compare different modulation formats for the TWDM-PON system.
- To measure performance improved TWDM-PON using parameters Q - factor and BER.

1.4 Scope of the Thesis

The scope of this research is covering work in the following aspects.

• TWDM-PON architecture and performance enhancing technologies for next generation PON technology.

• TWDM-PON system with the central office (CO) structure modified with the addition of the fiber Bragg grating (FBG) and an optical amplifier (EDFA) and optical power splitters using 1:4 splitter to distribute the signal to ONUs.

• The improved design of OLT using AWG for transmission of four different channels with 3 dB dynamic noise of AWG and 10 Gbps data are modulated with each channel.

• The improvement of the TWDM-PON performance due to the FBG and EDFA implementation is observed for different optical transmission distance and data rate and measured in terms of BER and value of Q factor.

• The performance various modulation formats, Carrier Suppressed Return to Zero (CSRZ), NRZ-DPSK, Duo Binary (DB), RZ-DPSK, and CSRZ-DPSK with 100 GHz to 50 GHz channel spacing a for TWDM-PON architecture is measured and analyzed in terms of BER and value of Q factor.

1.5 Thesis Contribution

This work focused on the AWG based Single laser source TWDM-PON system to reduce the cost and size of transmitter at the OLT. Different modulation techniques are analyzed in order to increase the transmission capacity under single laser source. Choosing the appropriate modulation formats is also the focus of this study. The system performance was analyzed in terms of Q- factor, input power, and received optical power and Minimum BER. In this work, we also made a performance comparison between EDFA, ROA, and SOA along with dispersion compensation technique at various transmission distances and input powers.

1.6 Methodology

In this research work, the TWDM-PON OLT setup features is designed with a single laser source in cascade with a phase modulator and an arrays waveguide grating (AWG), with the phase modulator customized using one RF source. The phase modulator produces a multicarrier signal, which AWG separates into many single wavelengths according to its routing configurations. AWG is a passing band periodical filter that divides the input wavelengths into four separate wavelengths. The performance of different modulation formats is evaluated on the proposed single laser source TWDM-PON network using FBGs for dispersion compensation and optical amplifiers. In order to tackle the dispersion problem and increase transmission distance, Fiber Bragg Grating FBG would be an appropriate dispersion compensation technique. The FBG technology outperforms other dispersion compensation technologies such as, the Dispersion Compensation Fiber (DCF) which has a high fiber attenuation, insertion loss and increases nonlinear effects. Thus, FBG could effectively compensate for the dispersion for the proposed system with an insignificant nonlinear effect, low loss, and low-cost fiber system. TWDM-PON would experience transmission losses in long-distance communication. Thus, the optical signal needs to be amplified by using optical amplifier in order to compensate for losses in the transmission by boosting the optical power, which in turn improves transmission reach and system performance. Commonly used optical amplifiers, SOA, RAMAN Amplifier and EDFA are considered for the analysis. SOA has a high gain bandwidth and a high noise figure. These amplifiers have higher nonlinear distortions in the form of self-phase modulation. The gain spectrum of the RAMAN amplifier is quite broad, and the shape of the gain spectrum can be changed by changing the number of pumps and their wavelength. RAMAN improves the noise figure by lowering the nonlinear effect penalty. EDFAs are low-noise amplifiers that are nearly polarization-insensitive. The other advantage of this optical amplifier is that it is capable of simultaneously amplifying many optical signals which is preferable for WDM systems.

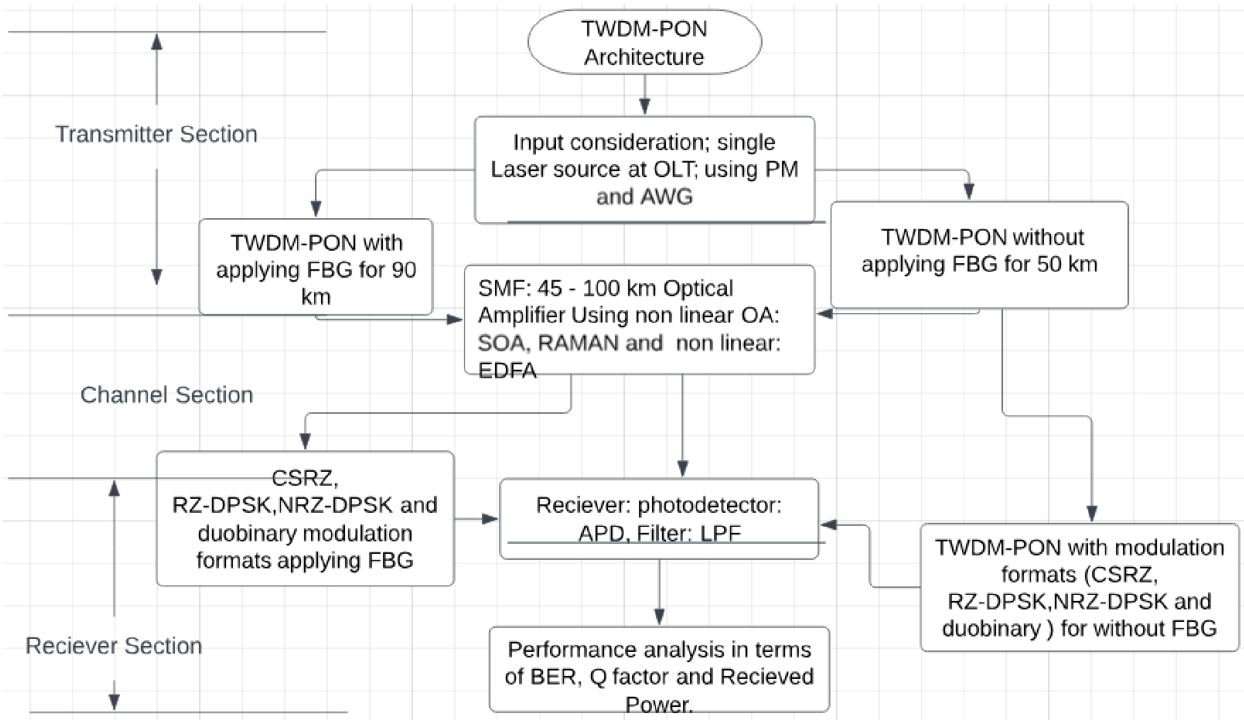

Figure 1.2 Methodology for the design of hybrid TWDM single laser source OLT System.

1.7 Significance of the Thesis

This research thesis significant contribution mainly falls on TWDM-PON architecture design and performance measure. After the completion of this study, cost-effective OLT design using AWG for a single laser transmitter which is based on the function of optical filters is also analyzed TWDM-PON architecture that can provide high data rate transmission for longer distance is evaluated and analyzed by introducing FBG dispersion compensation and different optical amplifiers. This work also identify an appropriate modulation format for TWDM-PON architecture with a single laser source that can provide high data rate transmission for longer distance.

1.8 Thesis Organization

This thesis is organized in five chapters. The first chapter includes the general overview of TDM/WDM PON and multi-wavelength Laser for OLT in TWDM. In the second chapter the related research works is presented. The third chapter includes the system design and analysis of TWDM-PON System Design using Multi Carrier Generation for single laser OLT. Chapter four includes the result and discussion of the Single Laser Source for OLT in TWDM system with different Modulation techniques and different modulation formats system using different performance comparison metrics. Chapter five finally includes the conclusion and recommendations.

Chapter 2

Literature Review

A. Fayad, Q. Alqhazaly, T. Cinkler, (2021)[12] This work uses four different wavelengths in the range of 1596 to 1603 nm, a fiber link of 40 km, and varies the value of the power optical splitter from 1:2, 1:4, 1:8, 1:16 and 1:32 to create NG-PON2 systems at 4x10Gbps. After design and simulation are complete, the outcomes are assessed in terms of optical spectrum, customer count, and optimal received power over sensitivity, surplus power margin, and maximum fibre span. The outcomes show that the suggested design is appropriate for implementing TWDM-PON. This study analyses numerous features for NG-PON2 needs based on ITU-T G.989 and simulates the fundamental TWDM-PON architecture for downstream signal. OptiSystem simulator tools are used to design, develop, and test a 40 km-long TWDM-PON system at 4 distinct wavelengths (1596, 1596.8, 1597.6, and 1598.2 nm). Based on optical spectrum, received power, surplus power margin, and maximum fiber span, the outcomes of the modular design for the downstream path were examined. This article achieves simulation results for both amplitude received power and excess power margin, the appropriate number of customers that can be provided for this TWDM network is 60. We obtained the following values for 60 customers: amplitude received power of -27.5 dBm, surplus power margin of 12 dB, and maximum fiber length of 100km.

Nani Fadzlina Naim1 , Fazryda Binti Zakaria et al.[13] Design And Performance Analysis Of Time And Wavelength Division Multiplexed Passive Optical Network (TWDM-PON). In this paper, they optimize the downstream transmission of eight channels WR-PON over 60 km and 40 km of standard single mode practical fibers (G.655 and G.652) with 10 Gb/s per channel and compared it with PS-ODN based passive optical network (PON). Both WR-PON and PS-PON are analyzed in detail under the specifications of deployed optical fibers like ITU-T G.652.A fiber, ITU-T G.652.B fiber. Next generation system performance is limited predominantly due to fiber dispersion and nonlinearities. Fiber nonlinearities and dispersions are mitigated and performance is enhanced by characterizing the system and optimizing optical launch power for both WR-PON and PS-PON. The number of users is increased in WR-ODN-PON architecture as compared to PS-ODN-PON, due to the low insertion loss of an AWG as compared to power splitter. As the number of ONU's (users) increases, the network operational cost reduces since the network devices are shared with more users. WR-PON is analyzed and performance is optimized by mitigating the fiber dispersion and nonlinearity under commercial fiber specifications for different modulation format.

Rahat Ullah1, Bo Liu [14], designs Cost Effective Scheme for OLT in Next Generation Passive Optical Access Network Based on Noise Free Optical Multi Carrier. This article discusses replacing a laser array at the optical line terminal (OLT) side of a PON with a multi-carrier source. The generated optical multi-carriers have the least amplitude difference (1.5dB) and a good tone to noise ratio (TNR) of above 20dB at 25-GHz frequency spacing. At the OLT, multi-carriers signal based multiplexed differential phase shift keying (DPSK) data from all the channels each having 10Gbps for downlink is transmitted through 25km single mode fiber. At the OLT, a 25km single mode fiber is used to transmit multiplexed differential phase shift keying (DPSK) data from all the channels, each of which has a downlink speed of 10Gbps. The proposed upgraded OLT is capable of transmitting 40 Gbps multiplexed data for four channels with each channels 10 Gbps from four ends in WDM-PON is used for downlink transmission is achieved 25 km fiber length with a minimum BER of 10^{-9}.

S. Rajalakshmi and T. Shankar (2019) [15] provide a performance analysis of different modulation formats for TWDM-PON based on reflective semiconductor optical amplifier (RSOA). Modulation formats NRZ, RZ, DB, NRZ-DPSK, RZ-DPSK and CSRZ-DPSK were analyzed for two types of receiver configuration, PIN photo detector and APD photo detector under different distance and data rates. The authors justify that CSRZ-DPSK gives a minimum BER performance and Q factor at the maximum distance of 100 Km than other modulation formats in downstream transmission. The study uses RSOA for an extended reach of the system, which has less performance when compared to other amplifiers, while using appropriate and efficient amplifiers for TWDM is an important issue. A. Fayad, Q. Alqhazaly, and T. Cinkler (2021) [16] examined the performance of the different modulation formats for TWDM-PON transmission systems under different channel spacings. NRZ-OOK, CSRZ, DB, MODB, QPSK and DQPSK modulation formats were compared for different transmission distances and bit rate. When designing TWDM-PON networks 50 GHz and 100 GHz channel spacing were considered. The study results indicated that, using DB modulation transmission distance of 130 km was achieved while the maximum bit rate was achieved by DQPSK modulation using both channel spacing.

UDWDM-PON has been designed and analyzed using FBG based dispersion compensation by Umesh et al (2018) [17]. This paper considered the use of FBG to obtain low dispersion and long transmission length with high quality factor at 10 Gbps and compared its performance for NRZ and DRZ modulation formats. The study found that the fiber Bragg grating provides better performance in the UDWDM-PON at data rate of 10 Gbps. It has been shown that the performance of DRZ based system is good as its decrement ratio in Q-factor is less and the span length is larger than that of NRZ based system. The authors use FBG to enhance the system performance and analyze the effect of NRZ and DRZ modulation formats only while, examining the performance of advance modulation formats is a very important issue.

Jan Latal et al (2015) [19] studied the performance of WDM-PON using different types of modulation formats NRZ, RZ, CSRZ, CRZ, DB, RZ-DPSK, NRZ-DPSK. In this article, the advantages of individual modulation types regarding bit rate change and link distance were examined. The individual modulation formats are then compared to the limitations of WDMPON-based access networks. The authors show that for bit rate 10 Gbps and link distances 1-50 km, it was observed, that modulation format DB achieved the best values up to 30 km. The results indicate that the data rate and the transmission distance performance of WDM is not efficient for the current demand; this shows the need for an improved design of TWDM with other elements. The above literature review indicates the need for the study of performance of different modulation formats for the improved hybrid passive optical network using dispersion compensation and optical amplifier.

Table 2.1 7 × 7 summery of Literature Review

Authors	Titles	Methods	Results	Limitations
Nani Fadzlina Naim et al. (2021)	Design of Multi-wavelength Laser for TDM/WDM PON Application	CW-laser with DMZM and 2 EDFA	Achieve 18 km TDM/WDM with multi wavelength	It needs OAs and optical splitter and combiners. Low fiber span

Norbert Zdravecky et al. (2022)	Performance Enhancement of DWDM Optical Fiber Communication Systems Based on Amplification Techniques	EDFA every 50 km, ROA and SOA with DCF	40 Gb/s transmission, EDFA scheme to achieve better BER values and ROA is relatively better BER than SOA	It achieves low Received optical power for the three amplifiers with different distance (-58.4 -58.97 dBm)
A. Fayad, Q. Alqhazaly, and T. Cinkler (2021)	performance of the different modulation formats for TWDM-PON transmission systems	NRZ-OOK, CSRZ, DB, MODB, QPSK and DQPSK modulation	DB modulation achieved maximum transmission distance	Analyze for 4 laser source twdm pon
Umesh et al (2019)	Performance Analysis of UDWDM Passive Optical Network with Enhanced Span Length using FBG based.	Fiber Bragg grating DWDM-PON at data rate of 10 Gbps NRZ and DRZ.	Fiber Bragg grating provides better performance. DRZ based system is good in Q-factor is less	advance modulation formats should be considered

Chapter 3

TWDM-PON System Design using Multi Carrier Generation for Single Laser OLT

This chapter discusses the overall system design and modeling of TWDM-PON system with a low cost OLT by applying Single laser source. The proposed architecture based on cascaded configuration of phase modulator and AWG description for the design of Single laser source along with the necessary mathematical expression is described. The different modulation formats in the transmitter section and optical amplifiers for better performance are discussed.

3.1 General System model of TWDM-PON Using Single Laser Source.

TWDM PON system uses both wavelength and time division multiple access. In such a system, multiple wavelengths coexist in the same ODN using wavelength division multiplexing, and each wavelength serves multiple ONUs with time division multiple access. At the OLT side a set of laser diodes such as continuous wave laser diodes operating at different wavelengths serve as downstream laser sources, followed by a WDM for multiplexing. The ODN distributes the light signal to users sharing the aggregated bandwidth. ODN consists of fiber and power splitter. The aim of the splitter utilized in ODN is to distribute power to all ONUs [20].

The basic TWDM-PON architecture is designed using four pairs of wavelengths as λ1, λ2 , λ3 and λ4 for downstream with a wavelength range of 1596–1603 nm based on ITU-T G.989.2, the downstream wavelengths are spaced 100 GHz and the aggregated bandwidth composed by multiplexing the individual downstream light signals using WDM Mux. Then multiplexed signal output from the Mux carry data with aggregate 10 Gbps or 40 Gbps are directed to ODN through Single Mode Fiber (SMF)OLT optical transmitter consists of Pseudo-Random Bit Sequence (PRBS) Generator that generates the data stream to be transmitted followed by different Pulse Generator. The line coded data modulates the optical light generated by continuous wave laser diode laser CW Laser externally using Mach-Zehnder Modulator.

The WDM MUX combines all different channel signals into one signal and transmits it through a 20 km fiber span. The WDM De-multiplexer (WDM DEMUX) with a frequency spacing of 100 GHz and a bandwidth of 40 GHz, which splits the signal into four different wavelengths and transmits toward their respective ONU using 1:4 passive splitter. Total 16 ONUs used in this work 4 ONUs share the same wavelength and but with different time slots.

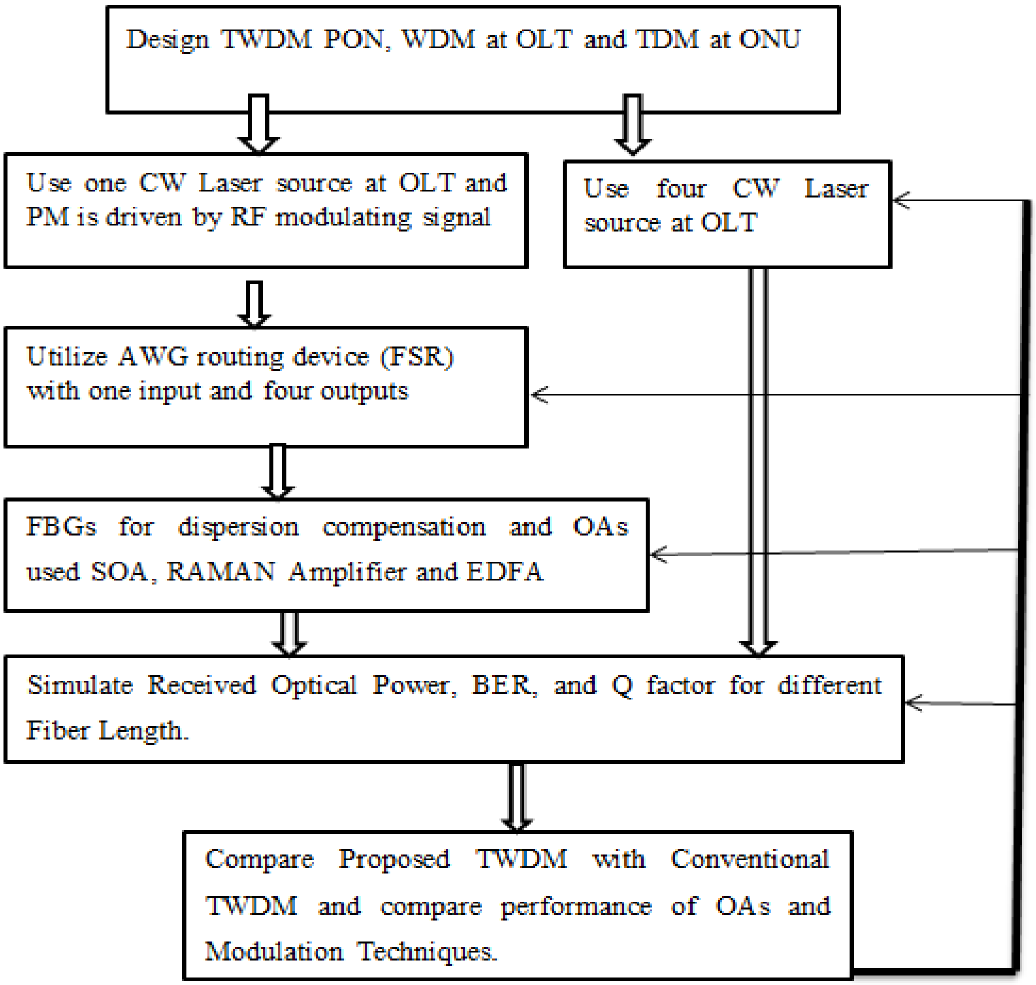

Figure 3.1 General procedures for the design of AWG Based TWDM-PON.

3.2 General System model of TDM-PON.

The figure below illustrates the TDM PON network's physical tree structure. The Optical Line Termination (OLT) at the Central Office (CO) transmits the data in the downstream traffic. OLT and ONU users are connected by an optical fiber via an optical Combiner/Splitter, a passive device that either combines or splits the signal going from OLT to ONU. The optical signal from each user is then combined using a power Combiner and is sent through the SMF of length varying from 20-100km. At the receiver's end a Power Splitter is used, which directs the optical data signals to each one of the ONU and it is synchronized with the specific time delay as given at OLT. The optoelectronic component is the ONU used at the user end.

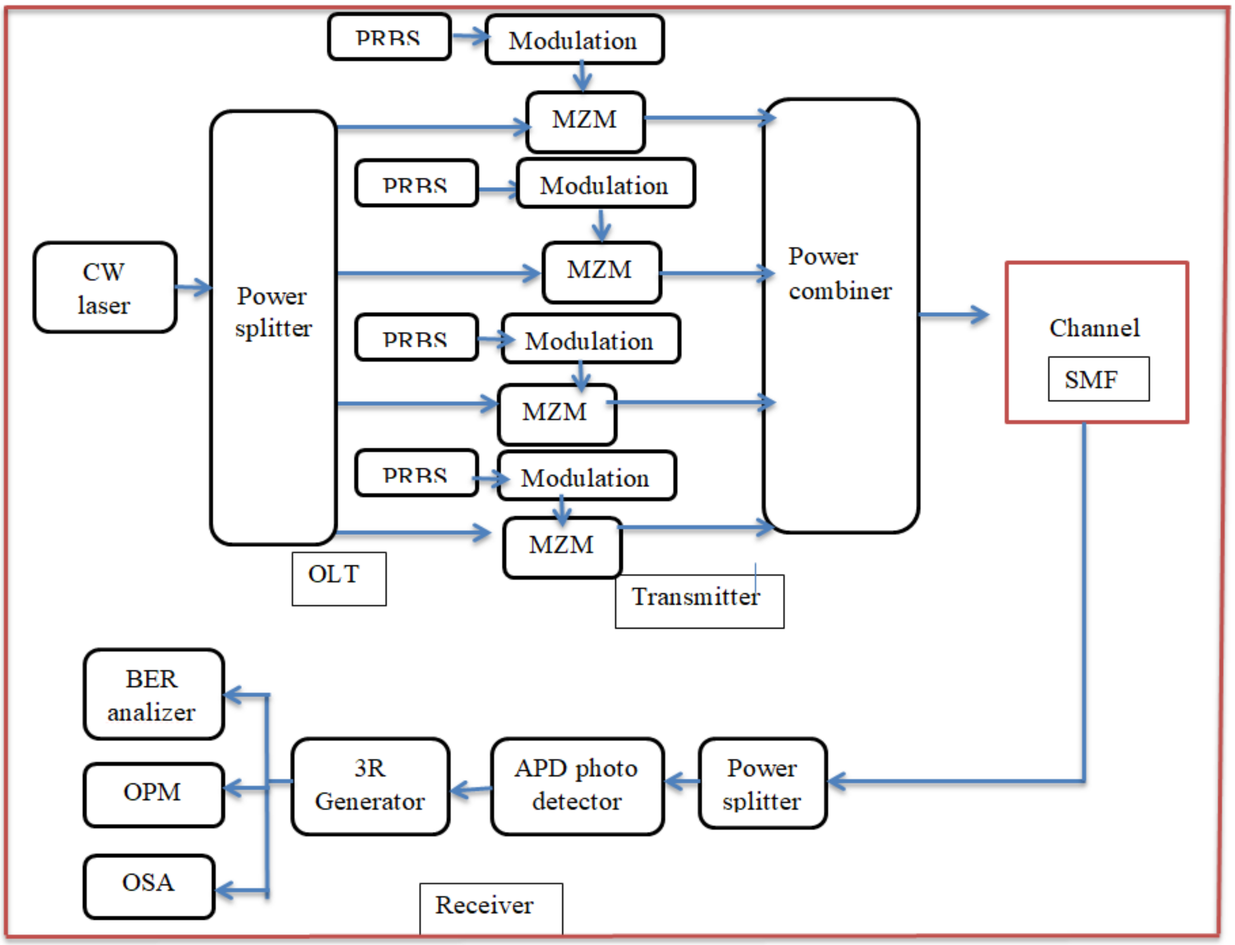

Figure 3.2 Block Diagram for TDM-PON Simulation Model.

3.3 General System model of WDM-PON.

The proposed architecture consists of three segments: Optical Line Terminal (OLT), ODN, and Optical Network Terminal (ONT). WDM-PONs use OLT is located in the CO of the provider and includes four transmitters to transmit the signals toward Optical Network Unit (ONU). We are using four wavelengths downstream which will require The ODN consists of 4:1 optical Multiplexer (MUX), Single-Mode Fiber (SMF), 1:4 Demultiplexer (DEMUX), and here, four power splitters were used with a splitting ratio of 1 × 4. The block diagram shown below describes the system model for downstream link of Single Laser Source WDM-PON.

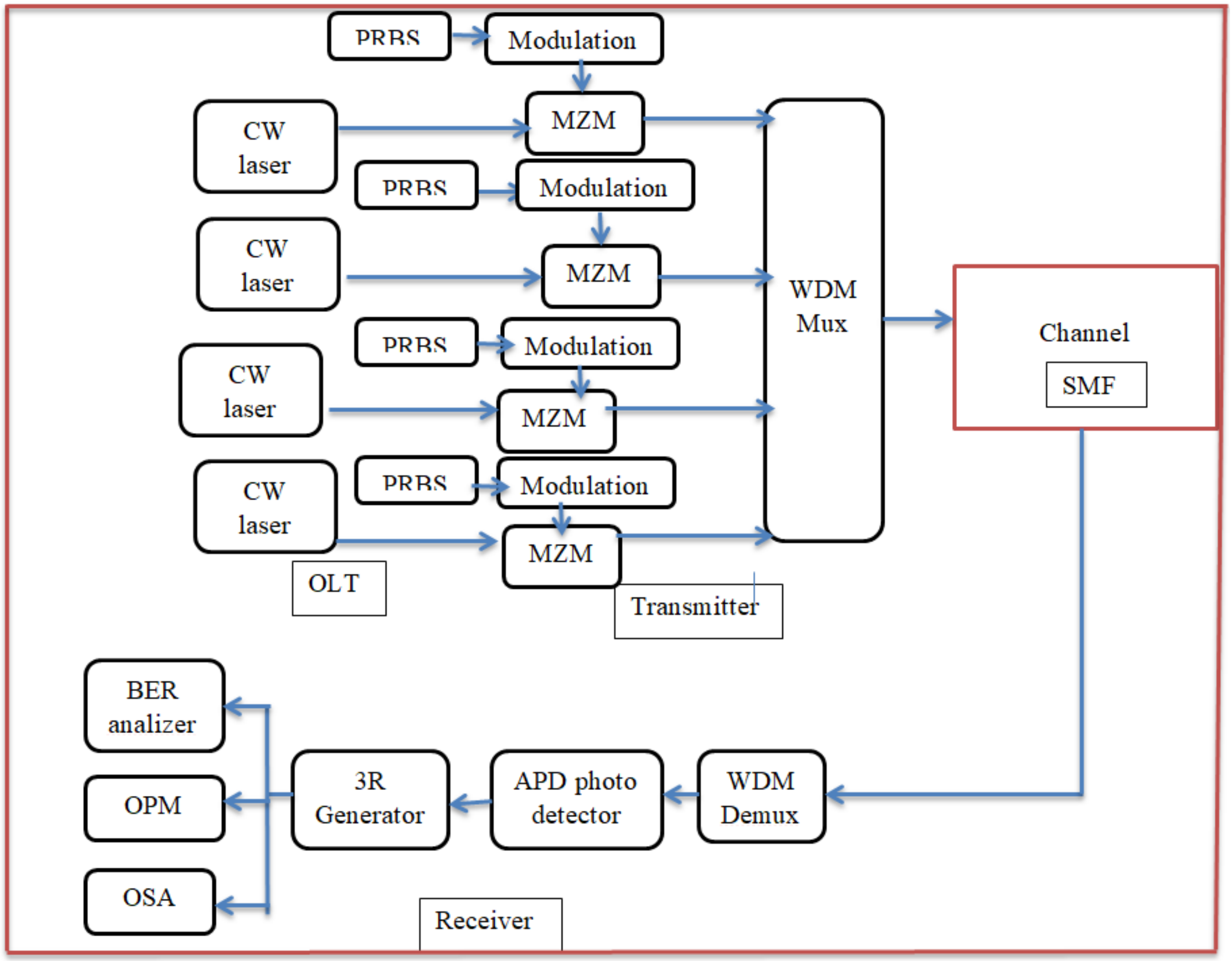

Figure 3.3 Block Diagram for WDM-PON Simulation Model.

3.4 General Block Diagram for TWDM-PON Using Single Laser Source.

The block diagram shown below describes the system model for downstream link of Single Laser Source TWDM-PON with different optical amplifiers and different Modulation techniques. And its performance has been measured with Q-factor and BER, by varying input power and length of the fiber.

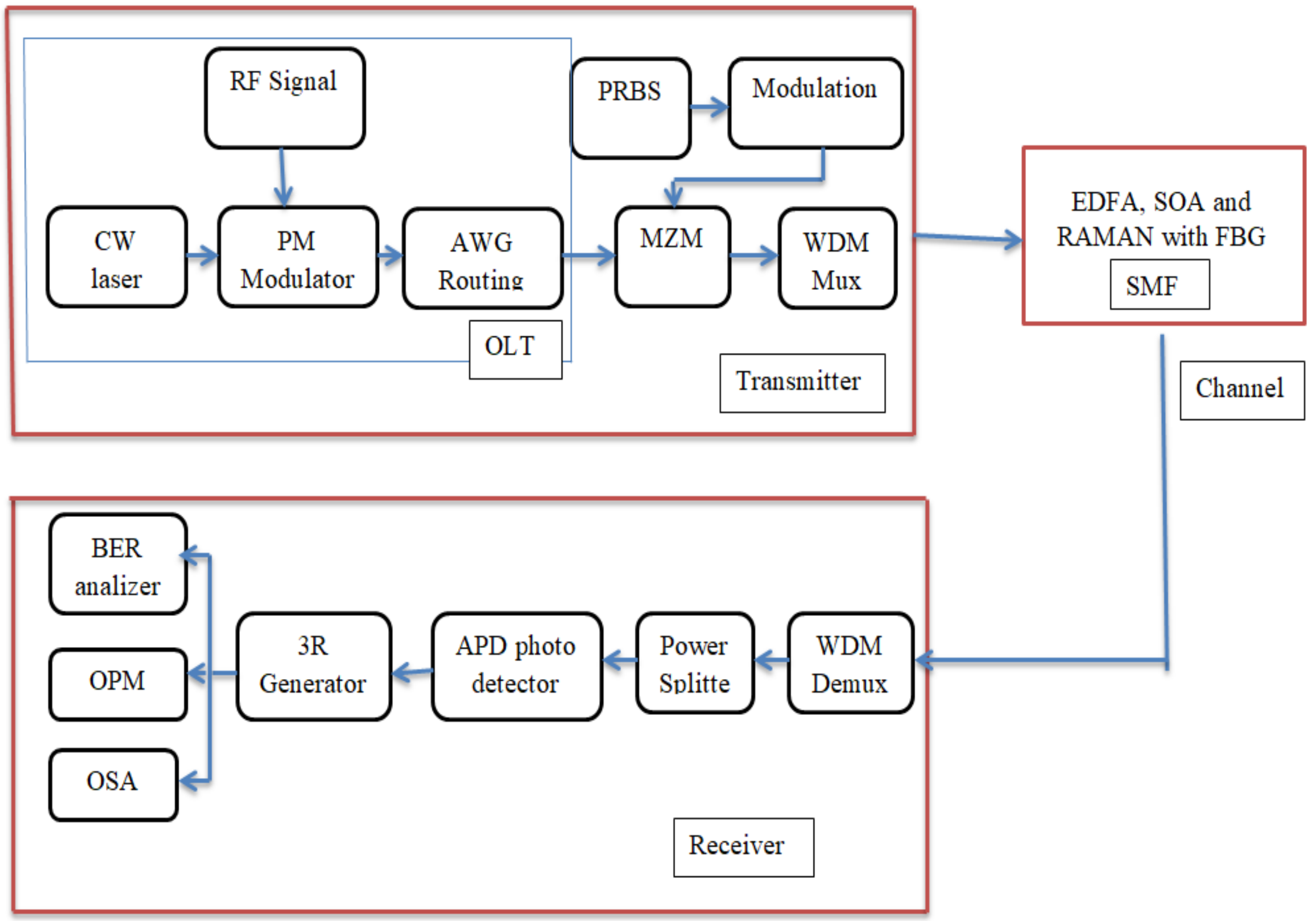

Figure 3.4 Block Diagram for single laser source AWG Based TWDM-PON Simulation Model.

3.4.1 OLT of TWDM-PON Using Single Laser Source

The laser array (laser sources) in OLT of TWDM-PON can be replaced by a single laser source which is directly connected with the phase modulator driven by radio frequency (RF) signal for generation of optical multi-carriers signal. RF signal is used for modulating the laser light. Phase modulator is driven by RF modulating signal with fixed frequency of f_s and CW-LD. AWG used as a routing device with one input and several outputs. AWG is a passive photonic device based on interferential phenomena having periodic behavior toward wavelength domain; it may have numerous inputs and outputs that perform the routing of wavelengths. At the input port of AWG, the incoming multicarrier signal routs toward a defined output port with specific wavelength.

The frequency at the output of RF source is expressed as;

$$f_{RFs} = R\sin(2\pi f_s t) \tag{3.1}$$

Where, R is the modulation index representing the rate of RF signal amplitude to the half-wave voltage.

The CW light wave generated from one narrow line width laser as seed source can be represented as;

$$\mathrm{E}_c = \mathrm{E}_o \exp\,(j2\pi \mathrm{f_c t}) \tag{3.2}$$

The phase modulator output can be represented as

$$\mathrm{E_{out}} = \mathrm{E}_c \exp\,(\mathrm{jR}2\pi \mathrm{f_s t})) \tag{3.3}$$

$$\mathrm{E_{out}} = \mathrm{E}_o \exp(\mathrm{j}2\pi \mathrm{f_c t}) \exp(\mathrm{jR}2\pi \mathrm{f_s t})) \tag{3.4}$$

Where, E_c is the output of the CW-LD source, and $\mathrm{E_{out}}$ is the output of the phase modulator.

The above expression can be expanded by the well-known Jacobi-Anger expansion to give the harmonics format with the multi-carriers expression as [21];

$$E_{\mathrm{out}} = E_0 \exp\,(j2\pi f_c t) \exp\,(j\pi R \sin\, 2\pi f_s t) \tag{3.5}$$

$$= E_0\{J_0(\pi R) \exp\,(j2\pi f_c t)$$

$$+J_1(\pi R)[\exp\,(j2\pi(f_c + f_s)t) - \exp\,(j2\pi(f_c - f_s)t)]$$

$$+J_2(\pi R)[\exp\,(j2\pi(f_c + 2f_s)t) - \exp\,(j2\pi(f_c - 2f_s)t)]$$

$$+J_3(\pi R)[\exp\,(j2\pi(f_c + 3f_s)t) - \exp\,(j2\pi(f_c - 3f_s)t)] + \cdots\}$$

$$= \sum_{n=-\infty}^{+\infty} J_n(\pi R) \exp\,[j2\pi(f_c + nf_s)] \tag{3.6}$$

Where, here $J_n(\pi R)$ is the first kind Bessel function of order n.

We can see that the output optical signal after the phase modulator generates several subcarriers with the frequency of $\mathrm{f_c}$+ $\mathrm{nf_s}$.

The frequency of RF source $\mathrm{f_s}$ is 100 GHz and The CW laser source is 187.1 THz. The generated subcarriers by the phase modulator have $\mathrm{f_c}$+ $\mathrm{nf_s}$ frequency where,

$$n = \pm 1, \pm 2 \ldots$$

The frequency spacing between each subcarrier is 100 GHz.

3.4.2 AWG Wavelength Routing

Depending on the signal's wavelength, the AWG routes the signal from an input port to an output port. Different inputs do not access the same output via the same wavelength, and one input of an AWG reaches different outputs by different wavelengths. Two Free Propagation Regions (FPR) star couplers one at the input and another at the output make up an AWG device. Waveguides of various lengths are arranged and used to connect the two FPR [22-24]. The following equations define the difference in the arrays' lengths (L) [23];

$$\Delta L = \frac{m\lambda}{n} \tag{3.7}$$

Where m is the order of the array, n is the index of refraction, and λ is the center operation wavelength. Input and output ports are ports connecting the first and second FPRs respectively. We here make use of the free spectral range (FSR) periodical routing property of AWGs to route more than one wavelength to each output port.

AWG used as a strictly non-blocking full-interconnect wavelength permutation router. As a wavelength router, a M × M AWG accepts M wavelengths from each input port and routes each wavelength to a different output port. Regardless of the input port, each optical frequency provides routing instructions. Wavelength λi entering at input port j is routed to output port

$$k = j + i - 1. \tag{3.8}$$

This shows that each output port receives M different wavelengths, one from each input port [25].

$$\text{If } j + i - 1 > M, \tag{3.9}$$

The frequencies are wrapped around (i.e., wavelength λi entering at input port j with $j + i - 1 > M$ is routed to output port $k = j + i - 1 - M$). In general, frequency λi, $i = 1, \ldots, M$, incident on input port j, $j = 1, \ldots, M$, is routed to output port $(j + i - 1) \bmod M$.

We can express the routing paths in matrix form, considering L as wavelength matrix. The rows of L representing input port and the columns indicate the output port. The elements λi of matrix L are the wavelengths routed by routing functions of AWG.

$$L = \begin{pmatrix} \lambda_1 & \lambda_2 & \lambda_3 & \cdots & \lambda_i & \cdots & \lambda_n \\ \lambda_n & \lambda_1 & \lambda_2 & \cdots & \lambda_{i-1} & \cdots & \lambda_{n-1} \\ \lambda_{n-1} & \lambda_n & \lambda_1 & \cdots & \lambda_{i-2} & \cdots & \lambda_{n-2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \lambda_2 & \lambda_3 & \lambda_4 & \cdots & \lambda_{i+1} & \cdots & \lambda_1 \end{pmatrix}_{i=1,2,\ldots,n} \quad (3.10)$$

In the case of this work 1 × 7 AWG wavelength router used in order to route the input multicarrier signal from PM to the output ports with certain wavelength spacing. Table 3.1 shows the routing table for 7 × 7 AWG based on the matrix given above.

Table 3.1 7 × 7 AWG and its routing table.

1 × 7 AWG

AWG Port	OUT 1	OUT 2	OUT 3	OUT 4	OUT 5	OUT 6	OUT 7
IN1	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
IN2	λ_7	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6
IN3	λ_6	λ_7	λ_1	λ_2	λ_3	λ_4	λ_5
IN4	λ_5	λ_6	λ_7	λ_1	λ_2	λ_3	λ_4
IN5	λ_4	λ_5	λ_6	λ_7	λ_1	λ_2	λ_3
IN6	λ_3	λ_4	λ_5	λ_6	λ_7	λ_1	λ_2
IN7	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_1

As shows in Table 3.1 above each input port of AWG gives different wavelengths for 7 different output ports. We have one multicarrier input which provides seven different wavelengths from λ_1 to λ_7 with 100GHz channel spacing. We are designing TWDM-PON with Four channels, thus four out port of AWG will be used four wavelength (λ_1 to λ_4).

3.4.3 Modulation Formats

One of the ways how to increase the capacity and scalability of transmission system is by using appropriate modulation format. Determining the appropriate type of modulation format for TWDM-PON has a great influence on the spectral efficiency and transmission capacity of the system. The first step to design the optical communication system is how the electrical signal would be converted into optical bit stream. There are choices for the modulation format of the resulting optical bit stream. We are investigating the performance of the TWDM-PON optical transmission system based on the transmission quality of the different modulation formats. The right choice of modulation format in optical fiber transmission systems can significantly influence system performance by increasing system capacity and reducing damage to the system transmission. Efficient modulation formats in addition to low-loss optical components and low noise optical amplifiers are key factors which allow high spectral efficiency, longer transmission, and high-capacity optical access networks [26]. In the past years, dominant optical modulations were Non-Return-to-Zero (NRZ) modulations and On-Off Keying (OOK) in systems with Direct Detection (DD) and in systems with Intensity Modulation (IM). Recent research into advanced optical modulations motivated demand for higher data rates, better system reliability, and optimal working conditions [27]. In optical fiber transmission, higher modulation orders can cause higher spectral efficiency. This shows modulation formats need to be evaluated considering their performance, the complexity of the implementation, as well as the bandwidth requirement of the transmission parts system [28]. Basic modulation formats such us, Non-Return to Zero (NRZ), Return to Zero (RZ) and Duo binary (DB) and advance modulation formats such as Non- Return to Zero-Differential Phase Shift Keying (NRZ-DPSK), Return to Zero- Differential Phase Shift Keying (RZ-DPSK), and Carrier Suppressed Return to Zero-Differential Phase Shift Keying (CSRZ-DPSK) performance in TWDM-PON system can be evaluated and compared with each other in order to choose the appropriate type of modulation format.

3.4.3.1. NRZ

NRZ is a modulation method that represents the 1 or 0 information of a digital logic signal utilizing two signal levels. A negative voltage corresponds to logic 0, and a positive value corresponds to logic 1. For NRZ transmissions, the baud rate the rate at which a symbol can change equals the bit rate. The optical pulse representing each 1 bit occupies the entire bit slot and does not drop to zero between two or more successive 1 bits. Optical NRZ modulation is considered a unipolar form of NRZ signaling and therefore has a strong Direct Current (DC) component which exceeds 50% of the total energy [29].

Adjacent NRZ pulses can be expressed as a sum:[29]

$$V_{o,n}(t) = \sum_{j=n-1}^{n+1} a_j S(t) \quad (3.11)$$

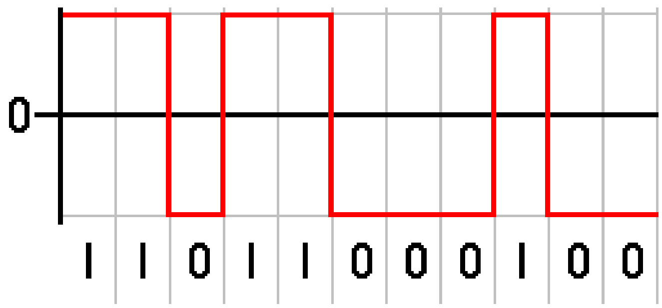

Figure 3.5 NRZ signaling pulses.

The figure above shows the binary signal is encoded using rectangular pulse amplitude modulation with polar NRZ code. In the NRZ format, the pulse remains on throughout the bit slot and its amplitude does not drop to zero between two or more successive 1 bits.

3.4.3.2. RZ

In the RZ formats, each pulse representing bit 1 is shorter than the bit slot, and its amplitude returns to zero before the bit duration is over. As a result, pulse width varies depending on the bit pattern, whereas it remains the same in the case of RZ format. RZ modulation formats are characterized by the fact that adjacent marks are separated by periods in which the magnitude returns to the low level [29]. The benefits of RZ are many: clock recovery of the transmitted data is easier, ISI effects are less pronounced, higher sensitivities can be achieved and penalties from coherent are lower [30].

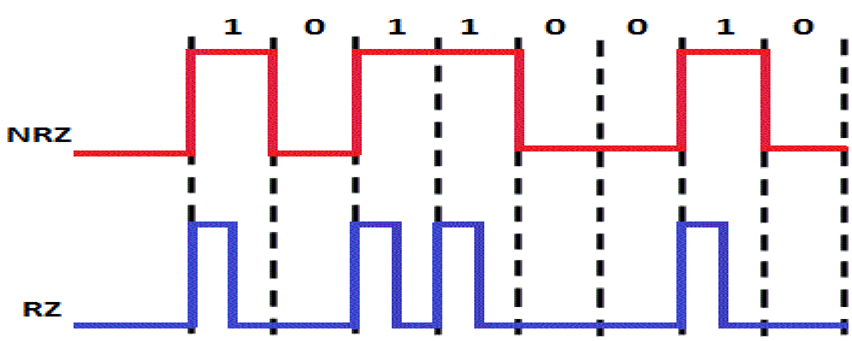

Figure 3.6 RZ and NRZ signaling pulses.

3.4.3.3. CSRZ

CS-RZ format is based on Return-to-Zero (RZ) format and links the separation of phase by π in each neighboring bit. In CS-RZ the pulse goes to zero between successive bits (RZ), and the field phase changes by π between neighboring bits.

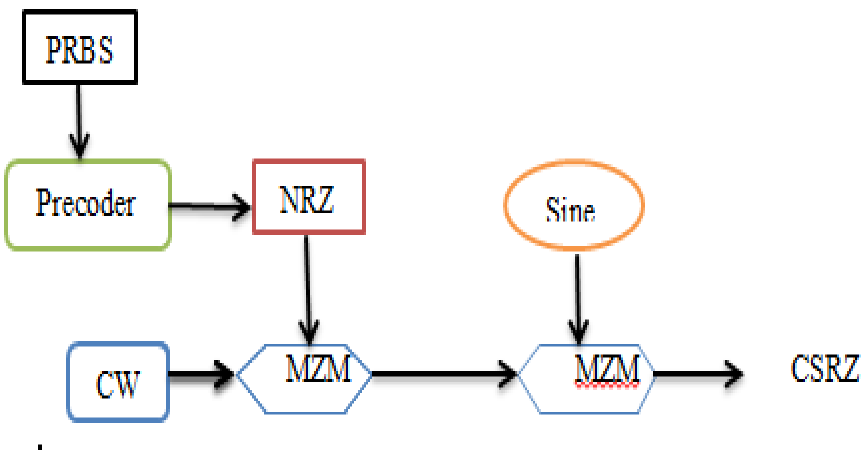

Figure 3.7 CS-RZ modulation format designs

The generation of a CSRZ optical signal requires two electro-optic modulators. The first Mach-Zehnder modulator encodes the NRZ data. The generated NRZ optical signal is modulated by the second Mach Zehnder modulator to generate a CSRZ optical signal. Standard form CSRZ is generated by a Mach–Zehnder modulator (MZM), driven by sinusoidal waves at half the bit rate BR. This gives rise to characteristically broad pulses [31]. The characteristic properties of a CSRZ signal are those to have a spectrum similar to that of an RZ signal, except that frequency peaks are shifted by BR/2 with respect to RZ.

3.4.3.4. RZ-DPSK

DPSK modulation format also belong PSK format, based on the relative phase between adjacent symbols that carry digital information "1" or "0." Commonly referred to as DPSK, it is in phase 0 or π represents information [31]. DPSK signal data is stored in the phase difference of adjacent bits in the received signal at the receiving end to deal with interference demodulation, the phase information into intensity information. RZ-DPSK is suitable for use in long range optical networks. Binary data are coded with zero or π shift phase between adjacent bits in this modulation. Optical pulse width is narrower than bit slot; therefore the signal goes to zero with each new bit slot [32].

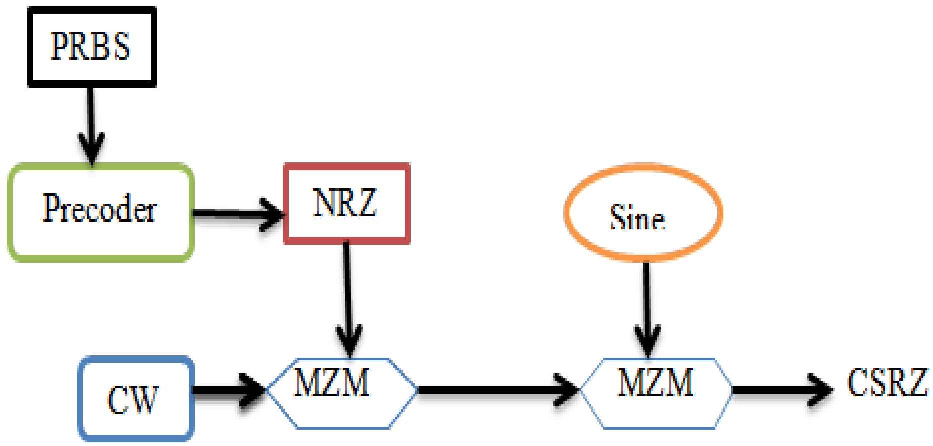

Figure 3.8 RZ-DPSK signal modulation format designs

RZ-DPSK signal is obtained by using a dual-drive MZM and two high-speed differential amplifiers. A very important characteristic of RZ-DPSK is that its signal power is always constant. Mach-Zehnder modulator is used for the phase modulation in the RZ-DPSK modulation.

3.4.3.5. NRZ-DPSK

NRZ-DPSK in light wave systems that consist of two parts consisting of transmitter and receiver which these parts used in transmitter and receiver of the proposed system, respectively. In the NRZ-DPSK transmitter, is a precoder modulation which has one-bit delay composes the NRZ signal. This signal which known as DPSK electrical signal is driven to a Mach-Zehender Modulator (MZM). In DPSK coder, NRZ data signal is converted by Apply modulation format NOR gate and then combined with one-bit delay by XOR gate. This decoded electrical signal is used for electro-optical phase modulator which generates DPSK optical signal. The digital one is represented by π phase shift consecutive data bits in the optical carrier. Digital zero does not cause any phase shift between consecutive data bits in the optical carrier. The important characteristics of NRZ-DPSK modulation are always constant power of optical sign [33].

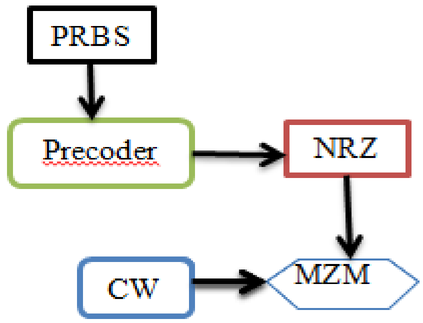

Figure 3.9 NRZ-DPSK signal modulation format designs

3.4.3.6. Duo binary

Duo binary (DB) modulation falls into the so-called modulation with memory. This modulation can obtain a signal (by the same modulation rate) which is more robust to chromatic dispersion (CD). This robustness is set by the fact, that adjacent logical values of one, between them is logical value zero, have an inverse phase. It's only good for nonlinear effects that aren't very strong. DB loses its advantages for stronger nonlinear effects. These signals are similar to CSRZ in the sense that some bits are flipped by phase with respect to others. However, partial response coding implies that these phase flips are positioned according to the transmitted bit pattern. Hence, partial response signals require an additional coding layer and different drive electronics than CSRZ [34].

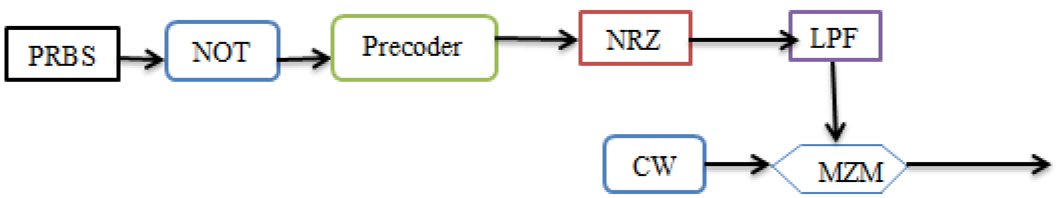

Figure 3.10 Duo binary signal modulation format designs

The schematic of the most common DB transmitter is shown in Fig. The raw data signal is first passed through a differential encoder. The differential encoder consists of an XOR gate and a 1-bit delay. The output of this logic step creates correlations between bits. The encoded sequence then passes through a LPF which has an approximate cutoff around R/4. The MZM transfer curve and modulated the CW light between the 0, V and 2V points

3.4.3.7. Mach-Zehnder Modulator

The MZM manipulates light through the electro-optic (EO) effect. When an electrical voltage is applied across an EO material such as LiNbO3, the effective refractive index of the waveguide changes. By applying a differential phase delay between two parallel paths, light intensity is modulated after recombining owing to constructive and destructive interference the output electric field of the MZM is [35],

$$E_{\text{out}}(t) = E_{\text{in}}(t)\cos\left(\frac{\pi}{2}\left(V_d(t) + \frac{V_{\text{bias}}}{2}\right)\right)\exp\left[i\frac{\pi V_{\text{bias}}}{4}\right] \tag{3.12}$$

Where E_{in} (t) is the input field, V_d (t) is the electrical driving voltage waveform and V_{bias} is the DC bias applied to the MZM arms [35].

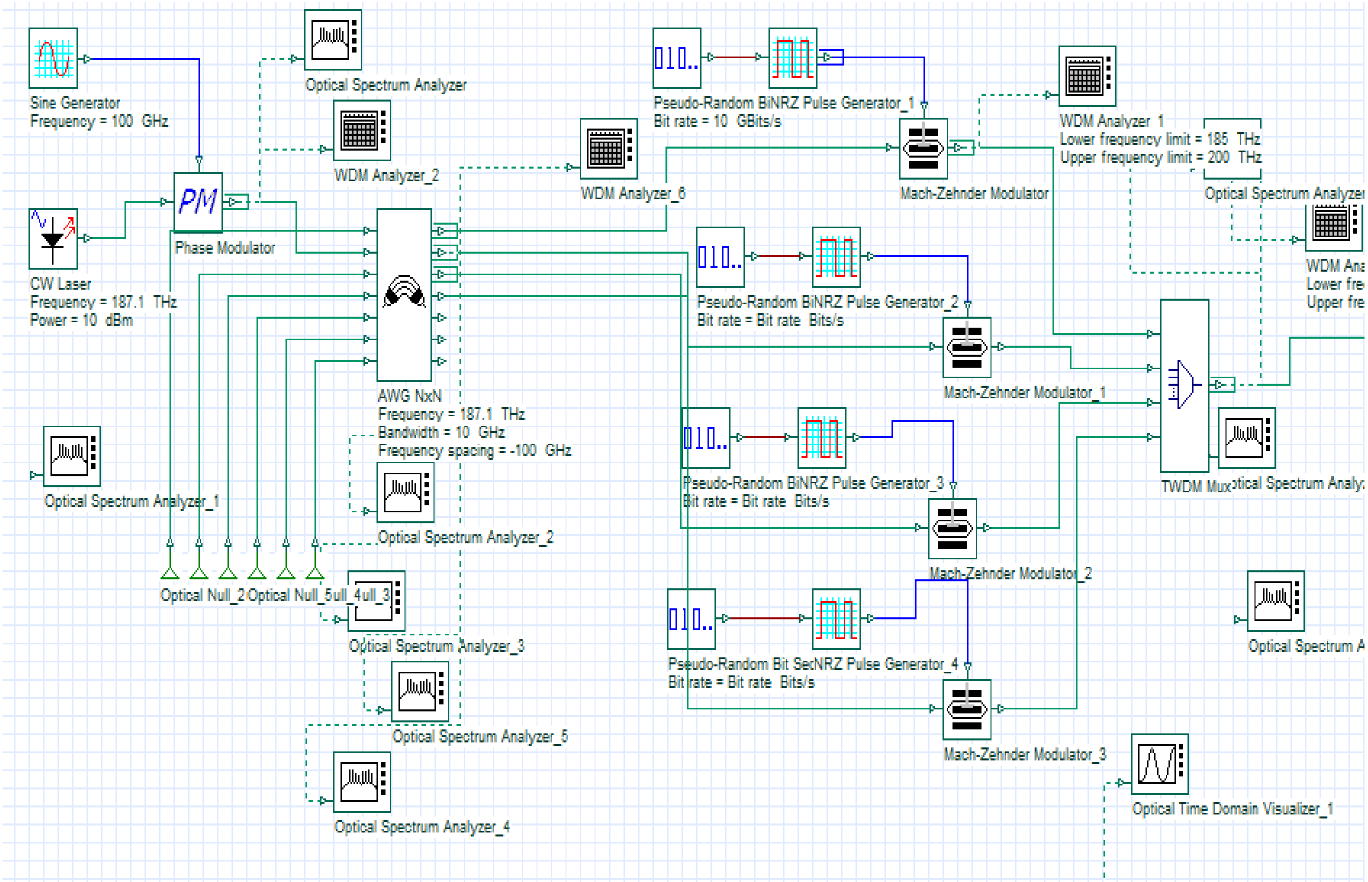

Figure 3.11 single laser Source TWDM-PON transmitter based on AWG design on Optisystem.

3.5 Dispersion Management

Dispersion Compensation (DC) using digital filters is a method used for removing phase distortions of an optical signal. Chromatic dispersion occurs when different wavelengths of light pulses are launched into the optical fiber. These pulses travel at different speeds due to the variation of refractive index with the wavelength. So they tend to get spread out in time after traveling for some distance in the optical fiber. This phenomenon of broadening the pulse width causes distortion of the transmitted signals and leads to errors in data receivers [36].

Dispersion increases along the fiber length. The general impact of Dispersion on the execution of a fiber optic framework is known as Inter Symbol Interference (ISI). Inter symbol interference happens when the pulse spreading caused by dispersion causes overlapping of pulses. Dispersion is of three types: Modal dispersion, Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) [37].

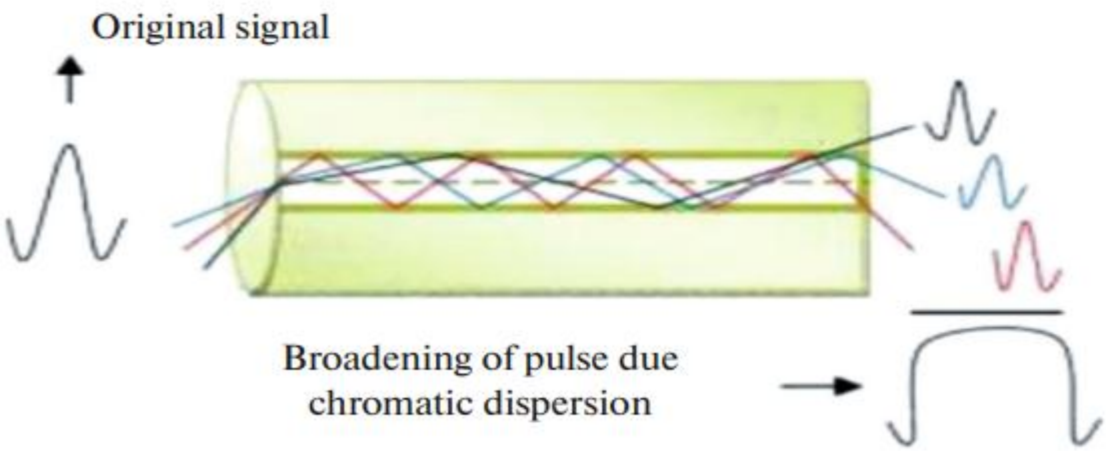

Figure 3.12 Dispersion effect on optical fiber.

3.5.1 FBG dispersion compensation

Todays, FBG is proving to be one of the most advanced technologies recommended to compensate Chromatic Dispersion in optical fibers overcoming challenges of the DCF technique because of its small size, low internal losses, negligible nonlinear effects, cost efficiency and high capacity in TWDM optical transmission system.

FBG is a type of distributed Bragg reflectors created in a small piece of optical fiber that reflects certain wavelength and transmits all other wavelengths. FBG is a single mode fiber that exposes the core to the periodic pattern of intense ultraviolet light. The exposure increase the refractive index and the pattern will create a fixed index modulation that is called Grating. This modulation is attained by adding a periodic variation to the core refractive index by exposing it to ultra-violet radiation, which generates a specific wavelength dielectric mirror. These resulted gratings reflect the propagated light in fiber according to Bragg wavelength λ_B which is specified as [38].

$$\lambda_B = 2n_{eff}\Lambda. \tag{3.13}$$

Where n_{eff} and Λ are the effective core refractive index and the grating period in optical fiber respectively. n_{eff} depends on the wavelength plus on the propagated light mode. The wavelength spacing between minimum and bandwidth is specified by

$$\Delta\lambda = \left[\frac{2\delta n_0 \eta}{\pi}\right]\lambda_B \tag{3.14}$$

Where, n_0 and η are the variation in refractive index and the fraction of power in the core respectively.

The periodic structure of a Fiber Bragg grating is ideal for compensating group velocity dispersion at many different wavelength variations. FBG was used to offset the effects of dispersion in the fiber optic network. Transmitting the signal for a distance of 40 Km and above over a SMF increases fiber dispersion. Thus, FBG could effectively compensate for the dispersion for the proposed system with an insignificant nonlinear effect, low loss, and low-cost fiber system.

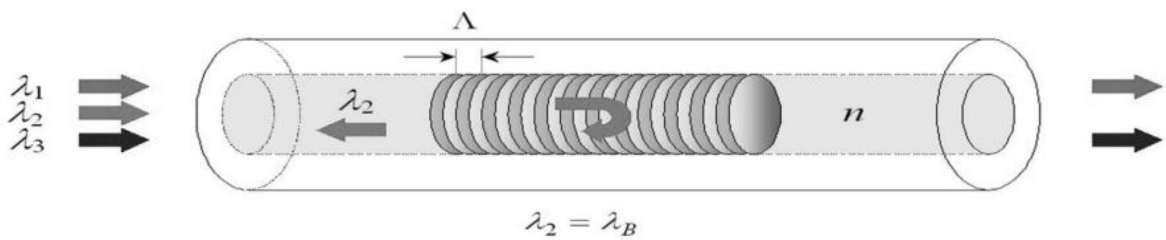

Figure 3.13 periodic structure of a Fiber Bragg Grating[39].

A fiber Bragg grating consists of a periodic modulation of the index of refraction along the core of an optical fiber thus creating a wavelength selective mirror as presented in Figure 3.11. FBGs are created by the exposition of a photosensitive fiber to an intensity pattern of UV light. In its basic form, the resulting grating reflects selectively the light guided by the optical fiber at the Bragg wavelength [39].

The length of the optical fiber increases from 20 Km to 100 Km the distortion increase at the optical signal as a result of dispersion. If the fiber dispersion at optical fiber is 16.75ps/nm/km, the total value of the dispersion along the 20 Km length will be

20 x 16.75 = 335 ps/nm

While the value when the length of the fiber increases to 40Km the dispersion is equal to:

40 x 16.75 = 670 ps/nm

670 ps/nm - 335 ps/nm = 335 ps/nm

50 x 16.75 = 837.5 ps/nm

For length of the fiber increases 100 km,

100 x 16.75 = 1675 ps/nm

1675 ps/nm - 837.5 ps/nm = 837.5 ps/nm

This shows that fiber dispersion at optical fiber increases 837.5 ps/nm as the transmission distance increases. FBG with a dispersion value of -837.5 ps/nm and above is needed in order to compensate this additional dispersion for 100 km.

3.6 Optical Amplifiers

Optical amplifiers are important elements in progressive fiber telecommunications networks. They offer the means to offset the losses produced by the fiber transmission medium, the optical fiber basic elements placed in the broadcast path and the power split at optical splitters. Optical amplifiers (OAs) are devices based on conventional laser principles. They receive one or more optical signals, each within a window of optical frequencies and simultaneously amplify all wavelengths. The transmission distance of any fiber-optic communication system is eventually limited by fiber losses. The loss limitation can be overcome by using optical amplifiers, which amplify the optical signal directly without requiring its conversion to the electric domain [40].

There are several types of OAs. Among them: erbium-doped fiber amplifier (EDFA), semiconductor optical amplifiers (SOA), and Raman amplifiers. OAs requires electrical or optical energy to excite the state of electron-hole pairs. Energy is typically provided by injecting electrical current (in SOA), or optical light in EDFA and Raman amplifiers. The EDFA OA is particularly attractive for WDM optical systems and it is widely used for these applications. On the other hand, SOAs are still at the R&D stage. Today, very few manufacturers produce them and the yield is very low [41]. Even though the technology of SOAs is based on the very well assessed semiconductor laser technology. Raman amplifiers are mainly used in long haul or ultra-long haul transmission systems with very high capacity where the signal degradation coming from the noise of the EDFAs is not tolerable or the required optical bandwidth is larger then what an EDFA can support [40].

3.6.1 EDFA

EDFA used as an optical amplifier to amplify the optical signal by stimulated emission principle as well as to transmit to a fiber optic communication using the erbium doped fiber. EDFA optimize the gain and output amplified optical power and obtained less noise figure and less output noise compared to input noise power. When these wavelengths propagate through the active fiber, erbium ions are excited and an incoming optical signal can be amplified by stimulated emission, releasing photon energy in the wavelength range 1530- 1565 nm (the C-band). By modifying the design of the amplifier, this range can also be shifted to longer wavelengths (the L-band). The basic structure of an EDFA consists of a coupling device, an erbium doped fiber and two isolators (one at each end). The fiber carrying the signal is connected via the isolator that suppresses optical reflections [42].

Gain of an erbium-doped fiber with a length of L is the ratio of the signal power at the fiber output to the signal power injected at the fiber input as [42]:

$$G = \frac{P_S(L)}{P_S(0)} \quad (3.15)$$

ASE noise generated during amplification process is added to the signal leading to decrease in signal to noise ratio (SNR) at the amplifier output. SNR reduction ratio from input to output of the amplifier is defined as Noise Figure (NF), which is also used for electronic amplifiers:

$$NF = \frac{(SNR)_{\mathrm{in}}}{(SNR)_{out}} \quad (3.16)$$

Noise Figure can also be expressed in terms of gain and spontaneous emission factor (n_{sp}) (or population inversion factor)

$$NF = 2n_{sp}\frac{(G-1)}{G} \approx 2n_{sp} \quad (3.17)$$

The power spectral density of spontaneous emission induced noise $S_{sp}(\nu)$ is a function of frequency and follows the emission spectrum of Er3+ ions :

$$S_{sp}(v) = (G-1)n_{sp}hv \quad (3.18)$$

EDFA avoids cross-gain saturation and provides amplification of individual channels in WDM systems. In silica fibers, spontaneous carrier lifetime is relatively long and this allows achieving high gain for a weak signal with low NF. Due to low NF the difference in signal-noise ratio at the input and output of the device under consideration. This is the main reason why EDFAs are so popular in optical amplification field [43].

3.6.2 SOA

A semiconductor optical amplifier is based on a semiconductor gain medium. SOAs are typically constructed in a small package and they work for 1310 nm and 1550 nm systems. The gain of an SOA is influenced by the input signal power and the internal noise generated by the amplification process so the output signal power increases the gain decreases. SOA accepts a wide range of input power and delivers constant output power because it has short carrier lifetime of about several tenths to several hundreds of picoseconds compared to several hundred microseconds to several milliseconds in EDFA's, means the SOA has fast gain dynamics. This saturation of gain can cause significant distortion in signal, which becomes more severe as the modulated signal bandwidth increases [44]. These effects are even more in multichannel systems where the saturation gain leads to inter-channel crosstalk.

The increase of the light intensity P in an SOA is determined by the gain g and the output spontaneous emission P_{sp} of the amplifier (both per unit length) [44],

$$\frac{dP}{dx} = gP + p_{\mathrm{sp}}, \tag{3.19}$$

Where P is light intensity in a given point within an amplifier. Gain here is the net modal gain. Provided we have no incoming light (P(x = 0) = Pin = 0), integrating (1) for an SOA of length L, we calculate the measured single-pass amplified spontaneous emission intensity $P_{\mathrm{ASE,L}}$ as [45],

$$P_{\mathrm{ASE,L}}(\lambda) = \eta_{\mathrm{c}} \frac{p_{\mathrm{sp}}(\lambda)}{g(\lambda)} \left(e^{g(\lambda)L} - 1\right), \tag{3.20}$$

Where η_c takes into account the output power coupling efficiency from the waveguide to the measurement equipment. Here, all the quantities have a wavelength dependency, therefore from (2), gain spectrum g(λ) can be calculated from measured $P_{\mathrm{ASE,L}}(\lambda)$ from SOAs of different length [40].

When light is injected into the SOA, changes occur in the carrier and photon densities within the active region of the SOA. These changes can be described using the rate equations. The gain medium of the amplifier is described by the material gain coefficient, g (per unit length) which is dependent on the carrier density N and is given by [45]. (From equation 3.23 – 3.27 [45-46])

$$g = \alpha_g (N - N_0), \tag{3.21}$$

Where N_0 is the carrier density at transparency point and α_g is the differential gain parameter. The net gain coefficient g_T is defined by

$$g_T = \Gamma \cdot g - \alpha_s, \tag{3.22}$$

Where α_s is the internal waveguide scattering loss, and Γ is the confinement factor which is the ratio between the cross sectional area of the active medium and the transverse area of the optical waveguide

The total gain G of an optical wave experienced at the location z of an SOA can be calculated

$$G = e^{g_r \cdot 2} \tag{3.23}$$

Assuming a constant carrier density at any given location z within the active region of the SOA.

Therefore, the average output power Pav over the length of the SOA becomes:

$$P_{avi} = \frac{1}{L} \int_0^L P_{in} G dz, \tag{3.46}$$

Where L is the length of the SOA and Pin is the input signal power. The average output power can be rewritten as [46];

$$P_{av} = P_{iv} \frac{e^{g_r L} - 1}{g_T \cdot L} \tag{3.25}$$

3.6.3 Raman amplifiers

Stimulated Raman Scattering (SRS) amplifiers are non-doped fiber amplifiers that employ high-power pumps to take advantage of the non-linear properties of the fiber. The pump and the signal are injected into the fiber through a fiber coupler. The signal is amplified by a process called stimulated Raman scattering (SRS), in which light is scattered by atoms from a lower wavelength to a higher wavelength. When sufficient pump power is present at a lower wavelength, stimulated scattering can happen in which a signal with a higher wavelength is amplified by Raman scattering from the pump signal. The energy is transferred from the pump beam to the signal beam through SRS as the two beams co-propagate inside the fiber SRS is a nonlinear interaction between the signal (higher wavelength) and the pump (lower wavelength) and can take place within any optical fiber. The pump and the signal beams counter-propagate in the backward-pumping configuration commonly used in practice. Raman amplifiers are called distribute or discrete, depending on their design. In the discrete case, a discrete device is made by spooling 1-2 km of an especially prepared fiber. The fiber is pumped at a wavelength near 1.45 μm for amplification of 1.55 μm signals.

3.7 Performance Evaluation Parameters

BER

BER is one of the performance metrics used to measure the performance of proposed system. It is the ratio of error bits to the total transmitted bits. Minimum acceptable error rate is 10-9, which suggests that, on the normal, one-bit error occurs for each billion bits sent. Too the high value of BER indicates that a slower rate would actually improve the total transmission time for a given amount of transmitted data.

The following formula can be used to compute BER

Quality(Q) Factor

Q-factor is a measure of overall system performance provided when two SNRs can be combined into a single quality. To calculate the total probability of error, we must consider for both of the signal-to noise ratios [46]. Q-factor is used to measure the quality of the optical signal by considering all factors like generated noise, the shape of the signal etc. It can be expressed as;

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \tag{3.26}$$

Where, I0 and I1 denote the current mean values for bit 0 and 1, and 1 and 0 denote the noise standard deviations for bit 1 and bit 0 respectively. The relation between BER and Q-factor can be expressed by:

$$BER = \frac{1}{2}\operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right) \tag{3.27}$$

Received Power

Received power is another parameter used in this research work. It is the amount of received power at the receiver. There is power loss when the signal propagates from the transmitter part to the receiver part. This power loss may occur at different nodes such as MZM, parabolic index MMF length, receiver APD and filter. The receiver power can be obtained as the difference between the transmitter powers to the power loss [46].

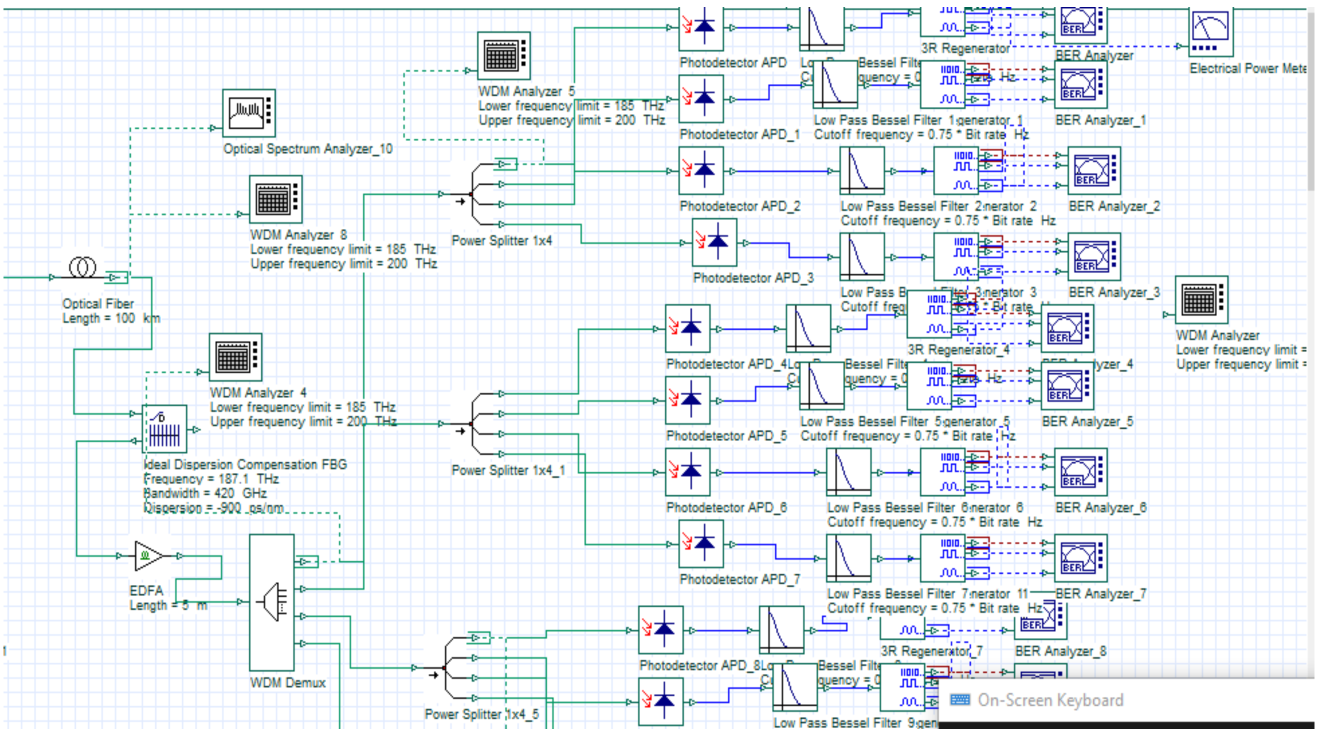

Figure 3.14 TWDM-PON for 100 km channel and ONU design on Opti system.

Transmission Link Design for Long Distance Transmission single laser source TWDM-PON System

Power margin is the difference between the minimal attainable optical power necessary at the receiver for a certain level of performance and the power sent at the beginning of system design with link losses occurring during transmission. Calculating the link's Power Budget (PB) and Power Margin (PM) will verify that the system architecture operates as intended. Power losses have been specified at different stages of the transmission path for downstream TWDM-PON.

Parameters taken from the data sheet for a link

- Data rate =R= 10 GHz.
- CW Laser spectral width = 0.05nm
- SM fiber dispersion at 1550nm = -20 ps/km-nm = -0.02 ns/km-nm
- Rise time of the receiver = 0.1 fsec
- Rise time of the transmitter = 0.1fsec
- Fiber loss = 0.2dB/km
- Transmitter power= 10 dBm
- Min Detectable power= -40 dBm
- Connector losses=0.5 dB
- Splice loss =0.5 * 40 =20 dB

Power Budget analysis

$$Total\ loss = \mathrm{PT} - \mathrm{PR} = 10dBm - (-30dBm) = 40dB$$

$$\propto_{\mathrm{fiber}} = Total\ loss - \propto_{\mathrm{connector}} - \propto_{\mathrm{splice}} - p_{\mathrm{safe\ margion}} \tag{3.28}$$

$$\propto_{\mathrm{fiber}} = 40dB - 2 \times (0.5)\ dB - 20\ dB - 4dB = 15dB$$

$$\mathrm{Lmax\ span\ length} = \frac{\propto \mathrm{fiber}}{\mathrm{Attenuation\ cof.of\ fiber}} \tag{3.29}$$

$$\mathrm{Lmax\ span\ length} = \frac{15\mathrm{dB}}{0.2\mathrm{dB/km}} = 75\ \mathrm{km}$$

Time Budget analysis

$$\sigma_{\mathrm{sys}} = 1.1\sqrt{\sigma\mathrm{f} + \sigma\mathrm{tr} + \sigma\mathrm{rr}} \tag{3.30}$$

But maximum allowed rise time of a system cannot be greater than 70% of the pulse duration of the data rate.

$$\sigma_{sys}=0.7 \times\frac{1}{R}$$

$$\sigma_{sys}=0.7 \times\frac{1}{10\ GHz} = 0.07\text{ns}$$

$$\sigma_{tr}= 0.5 \times t_{tr}= 0.05 \text{ fs}$$

$$\sigma_{rr}= 0.5 \times t_{rr}= 0.05 \text{ fs}$$

$$\sigma_{f}= \sqrt{(\frac{\sigma sys}{1.1})^2 - \sigma tr^2 - \sigma rr^2}$$

$$\sigma_{f}= \sqrt{(\frac{0.07}{1.1})^2 - 0.05\text{ fs}^2 - 0.05\text{ fs}^2}$$

$$\sigma_{f = 0.0636}$$

$$\sigma_{f}= D_{mat}\ \Delta\lambda L \quad (3.31)$$

$$L= \frac{\sigma f}{Dmat\ \Delta\lambda} = \frac{0.0636}{0.02 \times 0.05}$$

$$L=\frac{0.0636}{0.001}= 63.6 \text{ km}$$

From the Power Budget analysis and time budget analysis shows that the link is affected by dispersion, thus we should consider a dispersion compensation technique.

Power Budget (PB)

$$PR(dBm) = PT\ (dBm) - Losses(dB) \quad (3.32)$$

PR = PT – PMLoss − AWGLoss − MZMLoss − MuxLoss − SMFLoss − DmuxLoss – PSLoss (3.31)

PMLoss= PT – PM_{PR}

= 10 dBm – 3.47 dBm

=6.53 dB

AWGLoss= PM_{PR} – AWG_{PR}

= 3.47 dBm – (3.47)= 0 dB

MZMLoss = $AWG_{PR} - MZM_{PR}$

= 3.47dBm -(-36.94 dBm) = 40.41dB

MuxLoss = $MZM_{PR} - Mux_{PR}$

= -36.94 dBm -(-0.40dBm) = -36.54dB

Considering the attenuation in the optical fiber for 50km length.

SMFLoss = 0.2dB/km*50 km = 10 dB

DmuxLoss = $SMF_{PR} - Dmux_{PR}$

= - 10.4dBm - (-46.29dBm)= 36.29 dB

PSLoss = $Dmux_{PR} - PS_{PR}$ = -46.29dBm − (-52.39) = 6.1dB

PR = PT – PMLoss − AWGLoss − MZMLoss − MuxLoss − SMFLoss − DmuxLoss – PSLoss

PR = 10 - 6.53 dB - 0 dB - 40.41dB - (-36.54dB) -10 dB - 36.29 dB -6.1dB = -52.79dBm

$$\text{Power budget (PB)} = \text{PT (dBm)} - \text{PR(dBm)} \tag{3.33}$$

PB = 10 dBm – (-52.79dBm) = 62.79 dB

Therefore, power budget for single laser source TWDM-PON System design after calculating a link's power budget is 62.79 dB.

Chapter 4

Result and Discussion

In this chapter, the results obtained from the simulation of TWDM PON system by using Opti system software are presented. The performance analysis of TDM PON, WDM PON and TWDM PON system for different parameters is analyzed and discussed. The performance of TWDM PON using a single laser source analyzed and compared with four laser source using performance metrics of Min. BER and Q factor. Appropriate modulation format is analyzed by comparing in terms of different fiber length and different input optical power using Received optical power, Min. BER and Q factor. Then maximum transmission distance is analyzed without dispersion compensation technique and by applying a dispersion compensation technique of FBG using Min. BER and Q factor with constant input power and data rate.

At the end, the performance of the system is analyzed under different optical amplifiers; EDFA, Raman and SOA using received optical power, Q factor and Min. BER at various transmission distance and input power. The results of the carried out Optisystem simulations are available in the form of tables and figures after the establishment of the sets of beginning conditions.

Simulation Parameters

The parameter used for designing time and wave division multiplexing passive optical network (NG-PON2) system by opti-system simulations are carried out by considering the ITU-T G.989.2 network standard. The frequency of the laser, channel spacing, dispersion and attenuation of single mode fiber is based on ITU-T G.989.2.

Table 4.1 Simulation Parameter for TWDM PON using a single laser source

Parameters	**Value**
Optical source type	Continuous Wave (CW) laser
Bit Rate	10 Gb/s per channel
Laser Power	10 dBm
Channels	4
wavelength Channels	187 -187.3 THz
Optical fiber type	Single Mode

Optical fiber length	40 and 100 km
Optical fiber Attenuation	0.2d B/km
FBG dispersion	–900 ps/nm
EDFA length	5 m
ROA length	40 km
SOA inject current	0.15 A
Modulation format	CSRZ, DB, RZ-DPSK, NRZ-DPSK
Type of filter	LPF
Photo detector	APD

4.1 Performance Evaluation of TDM-PON and WDM-PON and a Hybrid TWDM-PON

Choosing a PON architecture that can provide high capacity and long reach for implementing optical fiber is done by doing a comparative analysis. The performance of TDM, WDM and TWDM-PON by varying fiber length while keeping other parameter constant has been discussed using Min BER, Q factor and Received Optical Power. We have analyzed and compared the performance that a hybrid TWDM-PON, TDM PON and WDM PON with a bit rate of 10 Gbps per wavelength and a input power of 10 dBm for all scenarios.

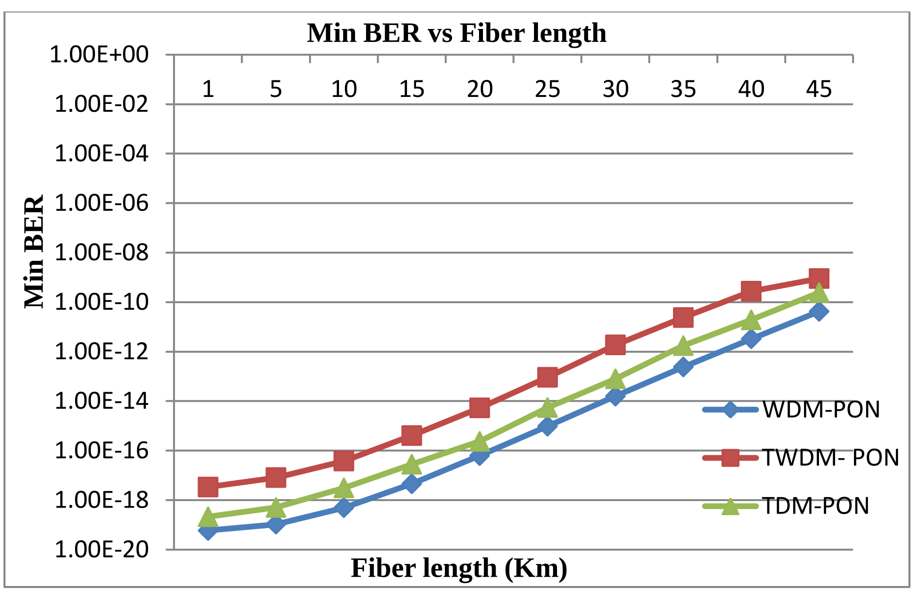

Figure 4.1 Plot for Min. BER performance comparisons of TDM-PON, WDM-PON and TWDM-PON.

TDM PON using a single wavelength and WDM-PON and hybrid TWDM-PON using four wavelengths for providing access for 16 users with a fiber length of 45 km has been analyzed. From figure 4.1 shows that the Min. BER of different PON architecture increases as transmission distance increases to 45 km. For all TWDM-PON, TDM PON and WDM PON Min. BER performance lowers as fiber length increases due to the loss in single-mode fiber and nonlinearity impact as the transmission distance increases. Here WDM-PON shows better performance than TDM-PON and TWDM-PON. The performance of hybrid TWDM-PON is lower than TDM-PON due to the loss and nonlinearity impact in WDM multiplexer and de multiplexer.

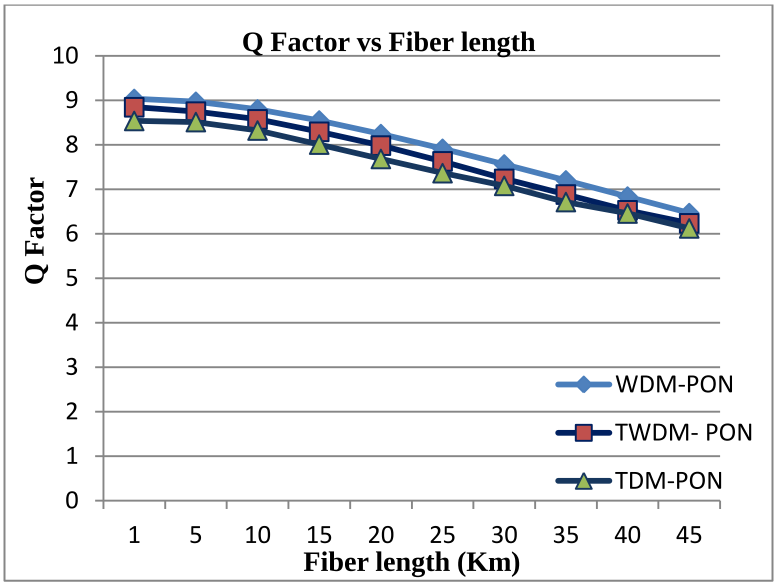

Figure 4. 2 Plot for Maximum Q Factor performance comparisons of TDM-PON, WDM-PON and TWDM-PON.

The comparison of PON architecture is necessary to improve transmission quality with maximum number of users. Q-factor decrease as the transmission distance increases when the power of CW laser is fixed at 10 dBm, for all cases. In all cases, the Q factor decreases as fiber length grows due to an increase in power loss and dispersion impact. As we can see from figure 4.1 the Q Factor performance of WDM-PON outperforms both TDM-PON and hybrid TWDM-PON. WDM-PON achieves a Q Factor of 6.46 at 45 km while TDM-PON and hybrid TWDM-PON gives a Q factor of 6.23 and 6.11 respectively.

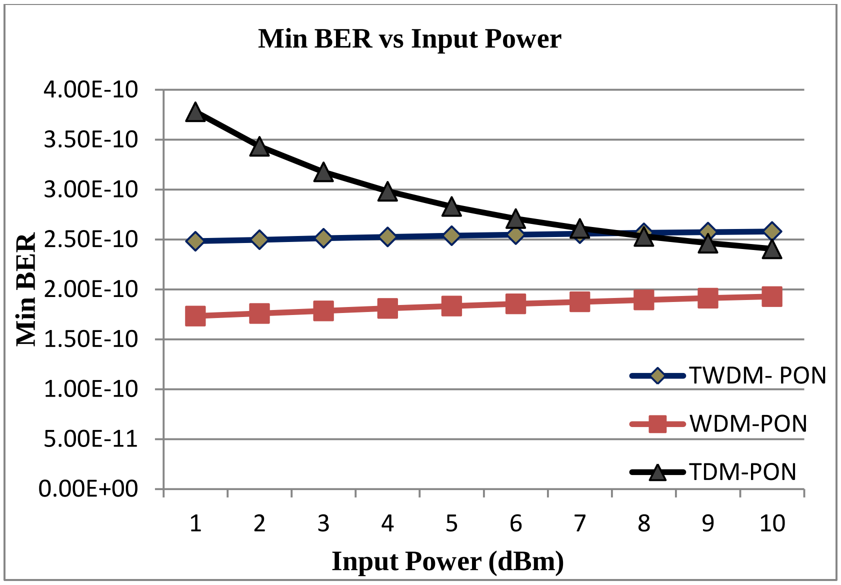

Figure 4.3 Plot for Min BER performance comparisons of TDM, WDM and TWDM-PON.

The performance of TDM-PON, WDM-PON and TWDM-PON in terms of Min BER with respect to the power transmitted by the CW laser source has been studied. We can see from figure 4.3 that when the power increases from 1 dBm to 10 dBm, Min BER decreases for TDM PON from 3.78E-10 to 2.41E-10, but for WDM PON and TWDM-PON gives almost constant performance as the input optical power increases. WDM PON performs better than TDM PON and TWDM-PON at all input power while TDM PON gives better Min BER at low CW laser power than TWDM-PON after 7 dBm input optical power. 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 the performance of Min BER.

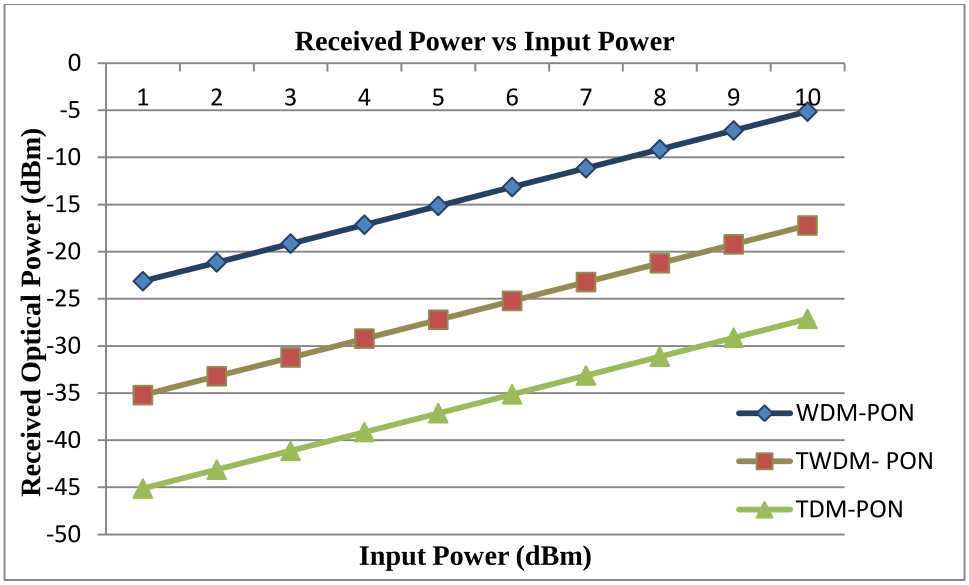

Figure 4.4 Plot for Received signal power performance comparisons of TDM and WDM as TWDM-PON.

As we have seen in figure 4.4, as the input optical power increases from 0 dBm to 10 dBm, the received optical signal power increases from -23.13 dBm to -5.14 dBm for WDM-PON and for TDM PON and TWDM-PON Received Optical Power at 45 km is -27.13 dBm and -17.2266 dBm. Here we have noticed that the received optical power for WDM-PON is better when it is compared with TDM PON and TWDM-PON. Here hybrid TWDM-PON shows better performance than TDM PON, Received Optical Power at 10 dbm input power is -17.2266 dbm and -27.13 dbm respectively. Since the optical source for TDM–PON is one and there are several power combiner and spilitters there is low ROP performance and in the case of TWDM-PON it is better than TDM-PON but due to additional components it has power loss during transmission.

Table 4.2 Comparison of WDM-PON, TDM PON and TWDM-PON

PON Type (at 45km and 10 dbm input power)	Received Optical Power (dBm)	Minimum BER	Maximum Q-Factor	Number of Users
TDM-PON	-27.13	2.41E-10	6.119989	16
WDM-PON	-5.14597	4.19E-11	6.463884	4
TWDM-PON	-17.2266	8.93E-10	6.232882	16

The above table 4.2 compares different PON types in terms of Received Optical Power, Min BER and Max Q Factor by varying input power and fiber lengths., an analysis has been done, from which it can be seen that for the same data rates, the performance of the unidirectional WDM-PON is better we noticed that Q-factors increase with power increase, while BER decrease. The comparison between TDM-PONs and hybrid TWDM-PONs justifies that TWDM-PONs are more advantageous and much convenient than TDM-PONs. WDM PON shows higher Received Optical Power of -5.14 dBm and Min BER of 4.19E-11, but it can only serve 4 ONUs (number of users). TWDM-PONs obtains acceptable Minimum BER of 8.93E-10 and Maximum Q- Factor 6.23 and provides 16 ONUs.

4.2 Performance of single laser source OLT on TWDM-PON

Single laser source at a wavelength of 1602.31nm (187.1THz) is used for hybrid TWDM-PON OLT and its line width is 10MHz, while the output power for the laser is kept at 10dBm. Sine Generator is used to generate RF modulating signal with fixed frequency of 100 GHz. The simulation results for the output of PM multi-carriers generation is shown in figure 4.5 below.

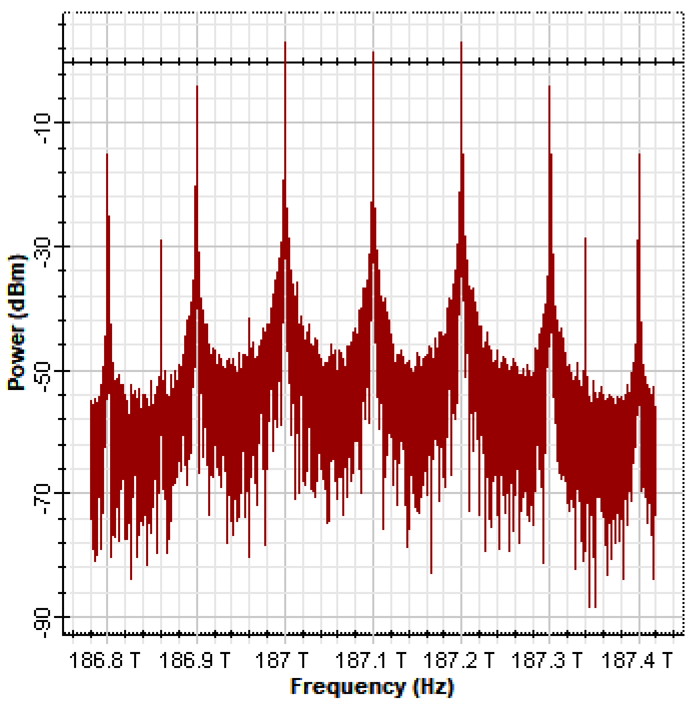

Figure 4.5 Generated multi-carrier output of PM.

As can observe from Figure 4.5, the obtained result, using one laser source with a wavelength of 1602.31nm is modulated by sine wave with a 100 GHz frequency from Radio frequency source. PM is used in multi-carriers generation, because it offers excellent stability of carriers. Furthermore no DC biasing is required. The PM modulator output generates multi-wavelength with seven different wavelengths (186.4 – 187.4 THz) with a frequency spacing of 100 GHz. We utilize AWG as a routing device with one input and seven outputs.

The AWG forwards the signal at an input port to an output port, depending on the wavelength of the signal. One multicarrier input from the PM which provides seven different wavelengths from 186.4 – 187.4 THz. Thus AWG routs each wavelength to the output with 100 GHz frequency spacing. AWG acts as an array of filters that allows a specific wavelength to pass at a defined output port. Here we need four wavelengths for creating four channels, thus the wavelengths from 187 to 187.3 THz obtained from AWG.

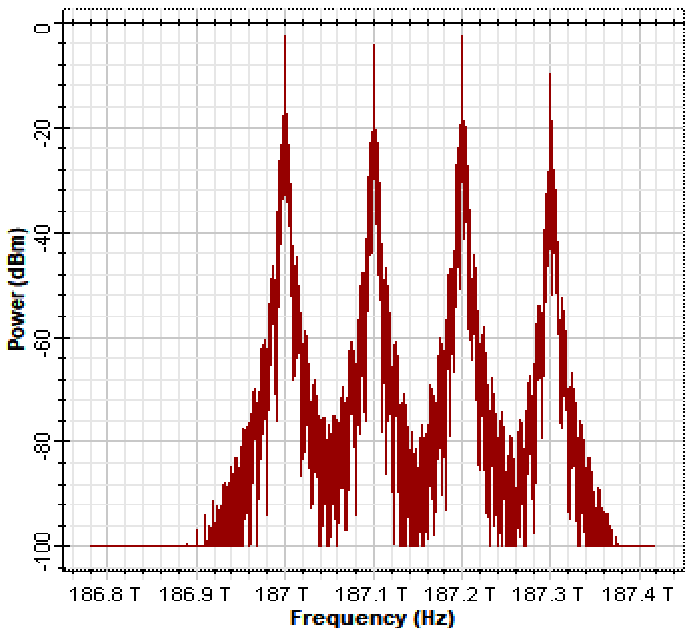

Figure 4.6 four multiplexed channels after AWG filtering.

four multi-carrier signal which are modulated using different modulation formats signal at frequency of 187 THz, 187.1 THz, 187.2THz, and 187.3 THz for transmission.. After optical modulation WDM Multiplexer is used to multiplex four channels. Figure 4.6 shows four multiplexed channels transmitted after AWG filtering.

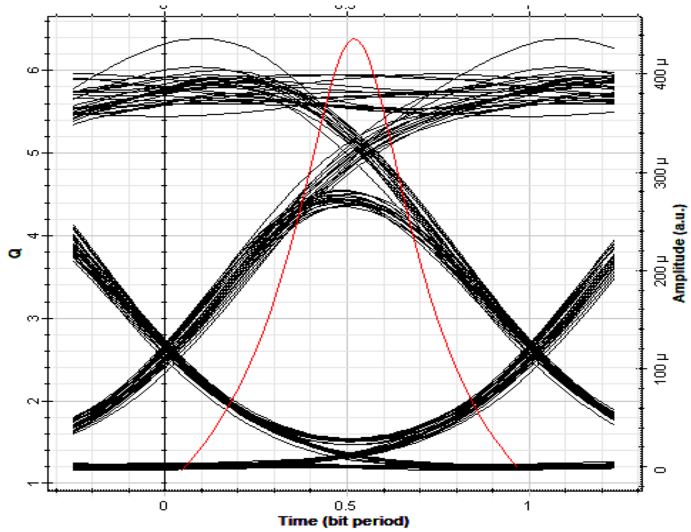

Figure 4.7 Eye diagram for single laser source TWDM.

The eye patterns for a single laser source TWDM at 45 km with a 10 dBm input optical power of CW laser are shown in Figure 4.7. The system is more efficient the clearer the eye diagram is. A clear eye diagram showed how effective a system was; going forwards, the suggested architecture's resultant diagrams show a clear eye pattern with good heights and Q-factors.

4.3 BER and Q factor performance of single laser source OLT on TWDM-PON.

Performance analysis of TWDM-PON based on single laser source at the OLT is done by sweeping different parameter. The simulation analysis is done by increasing fiber length from 1km to 45 km and input optical power from 0 dBm to 10 dBm.

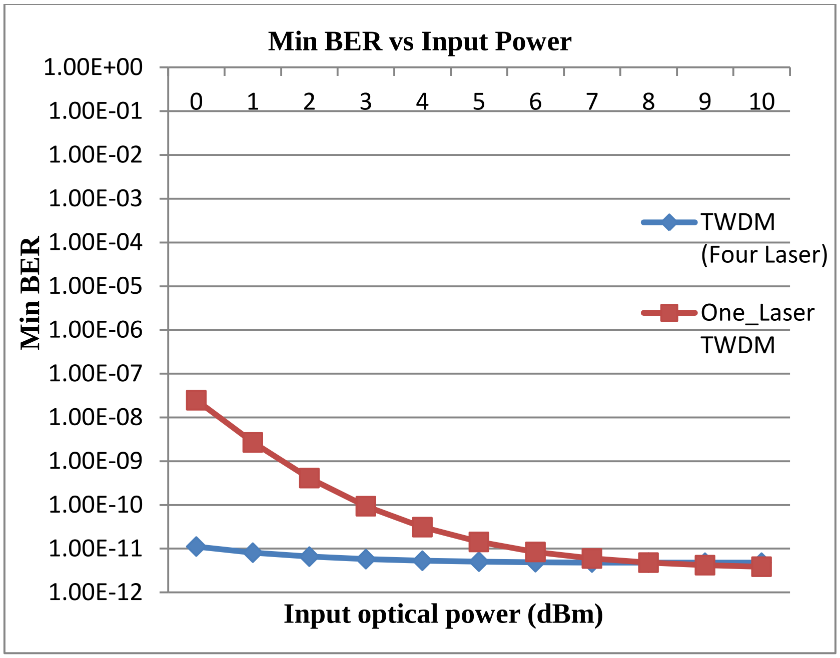

Figure 4.8 Min BER performance comparison for TWDM-PON with single laser and four laser sources.

It is observed in figure 4.8 that the Minimum BER value observed for input power reached up to 10 dBm for fixed value of transmission distance of 45 km and data rates of 10Gbps for 16 users for both four laser and single laser TWDM-PON. For low CW laser power TWDM-PON with four laser sources gives a better result, since each wavelength is generated by separate laser source while in the single laser source only one laser source provide power for four different channels. TWDM-PON with single laser source If we increases the input power beyond 7 dBm the Minimum BER performance of single laser source TWDM-PON is same as four laser source TWDM-PON. In the case of Single laser source TWDM-PON, one CW-Laser source provides for four different channels Min. BER improves as the input optical power increases while in the case of four lasers each lasers provide for one cannels the improvement of Min BER is lower.

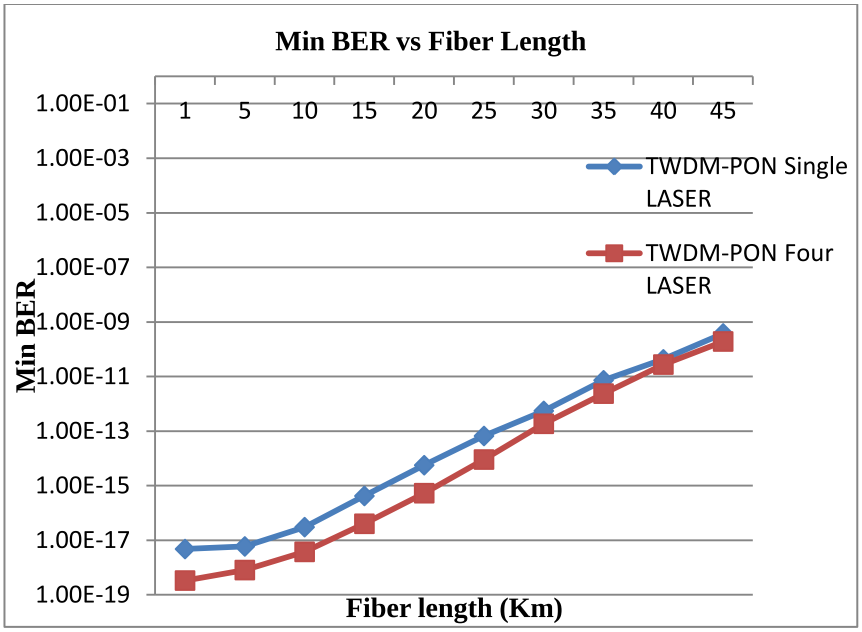

Figure 4.9 Min BER performance comparison in terms of fiber length for TWDM-PON with single laser and four laser sources.

Figure 4.9 and Table 4.3 shows the Minimum BER performance of single laser source and conventional four laser source at different positions by changing fiber length with ten iterations ranging from 1 km to 45 km while keeping all other parameters constant.

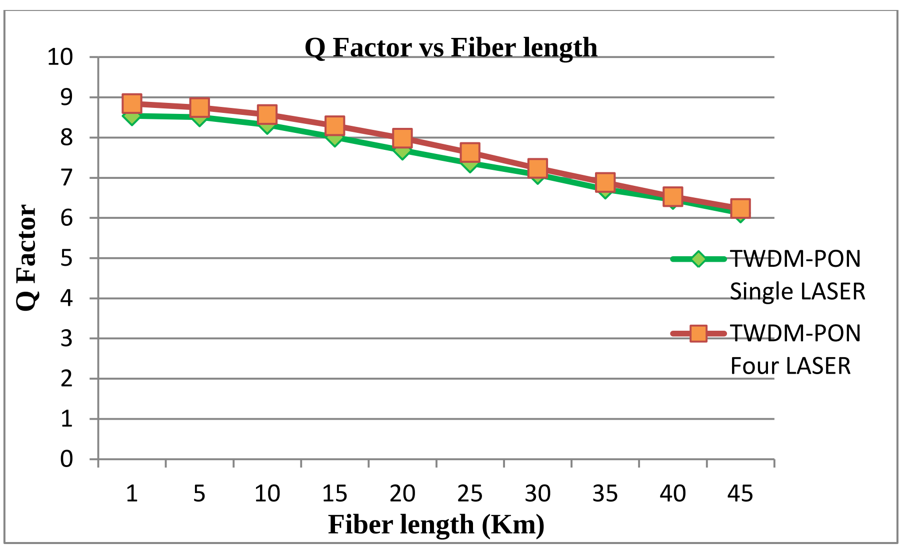

Figure 4.10 Max Q factor performance comparisons in terms of fiber length for TWDM-PON with single laser and four laser sources.

Table 4.3 Comparison of TWDM PON single laser source and TWDM-PON with four laser source

PON Type (at 45km and 10 dBm input power)	Received Optical Power (dBm)	Minimum BER	Maximum Q-Factor	Number of Users
TWDM-PON single laser source	-5.14597	3.80E-10	6.11	16
TWDM-PON Four laser sources	-17.2266	1.93E-10	6.23	16

As the fiber length increases from1 km to 45 km, the Min BER performance increases for both cases. As we have seen from figures 4.9 and 4.10, as the length of the optical fiber increases, the Max Q factor declines for both cases since as the fiber length increases the power loss and dispersion effect during transmission also increases. At 45 km single laser source TWDM-PON achieves Max Q factor of 6.119989 for 10 dBm input optical power and TWDM-PON with four laser sources gives Q factor of 6.232882. Here we can see that using single laser source provides good performance which is equivalent to using four laser sources.

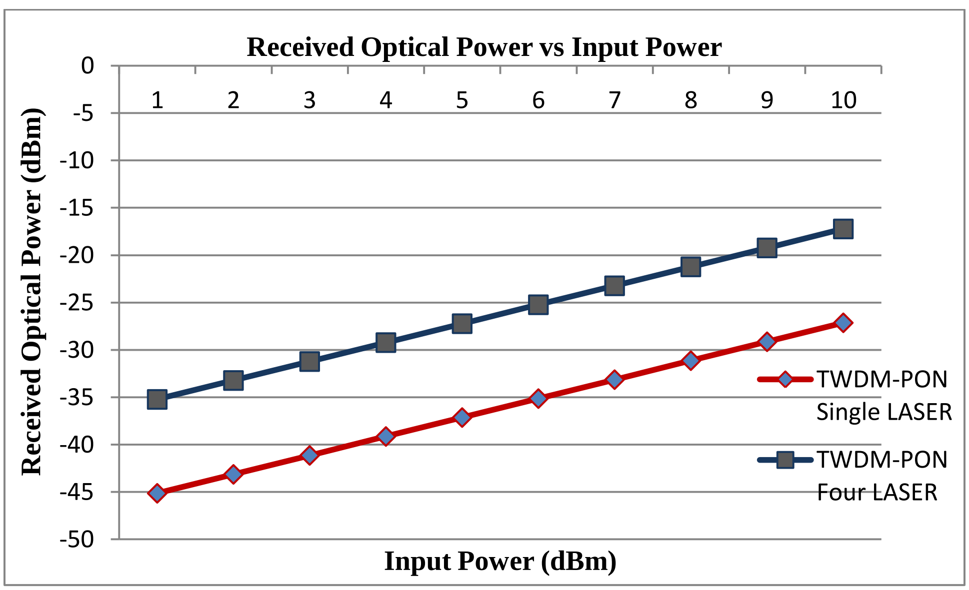

Figure 4.11 Received Optical Power performance comparison with respect to input optical power for TWDM-PON with single laser and four laser sources.

As the results show in figure 4.11 the Received optical signal power increases as the input optical power increases. Because power loss during transmission compensated with increasing input power. The Received optical signal power increase from -35.21 dBm to -17.22 dBm in case of TWDM utilizing four laser source , the optical signal power increases from -45.12 dBm to -27.12 dBm in the case of TWDM using single laser source as the input power increases from 0 dBm to 10 dBm for all cases. We can see from the simulation results in figure 4.11 that utilizing TWDM utilizing four laser source for all iterations results higher received optical signal power than TWDM using single laser source since TWDM with four lasers each lasers provide each channels while in single laser source one laser serves four different channels.

4.4 Performance Evaluations of Different Modulation Formats for single laser source of TWDM system.

The performance of different Modulation Formats has been discussed in TWDM- PON system by varying input optical power and fiber lengths by keeping other parameters constant. The effect modulation formats is analyzed in terms of Min BER, Q factor, Received Optical Power and Maximum OSNR. It is compared with all the six types of modulation formats, NRZ, RZ, NRZ-DPSK, RZ-DPSK, CSRZ and Duo binary.

The performance comparison of different modulation formats for achieving the maximum transmission distance, which can be achieved under the specific input optical power and bit rate. The performance evaluation is done for all the six modulation formats in terms of performance parameters like BER and Q factor. Simulations are carried out for various values of transmission distance ranging from 5 to 50 km without using any dispersion compensation techniques.

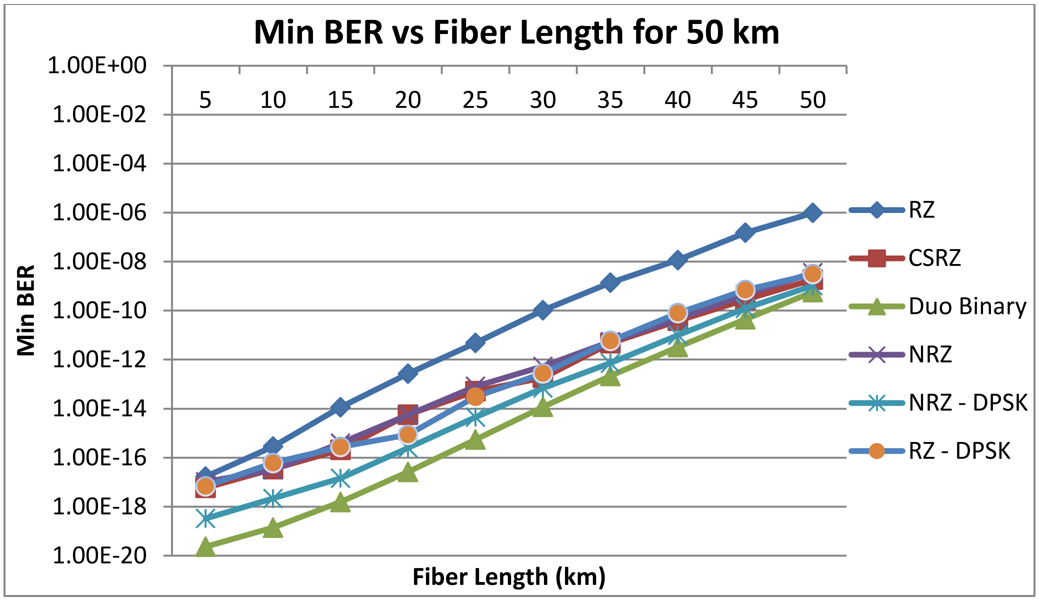

Figure 4.12 Min BER performance comparison of different modulation formats for TWDM-PON with single laser.

From figure 4.12, it is observed that when transmission distance increases Min BER also increases in the range of 50km for all modulation types. Duo Binary modulation format shows better performance in achieving 5.75 E-10 Min BER at 50 km transmission distance. While other modulation format gives a Min BER higher than 10^{-09}. This means that Duo Binary modulation format is highly tolerant to nonlinear effects. It is also seen that CS-RZ and NRZ-DPSK format is less affected by nonlinearity.

Table 4.4 Comparison of different modulation formats for TWDM-PON with single laser

Modulation format	Maximum transmission distance with BER of 10^{-10} , 50 km	Q - factor	Min BER
DB	50	5.981209	5.75E-10
NRZ-DPSK	49	5.968077	1.76E-10
CSRZ	49	5.869761	2.77E-10
RZ-DPSK	46	5.784959	7.86E-10
NRZ	46	5.756689	1.02E-10
RZ	35	4.824711	6.64E-10

We evaluated performance of all modulation formats NRZ, RZ, NRZ-DPSK, RZ-DPSK, CSRZ and Duo binary in system without dispersion compensation. Maximal transmission distances obtained by each format at constant input optical power of 10 dBm are shown in Table 4.4. As one can see, the best performance is demonstrated by Duo binary, NRZ-DPSK and CSRZ-DPSK. The maximum transmission distance achieved is around 50 km with a Min BER of 10^{-10}. The results of NRZ and RZ-DPSK are also quite good the maximum distance reach is above 45 km. while RZ shows very low performance when it is compared with others.

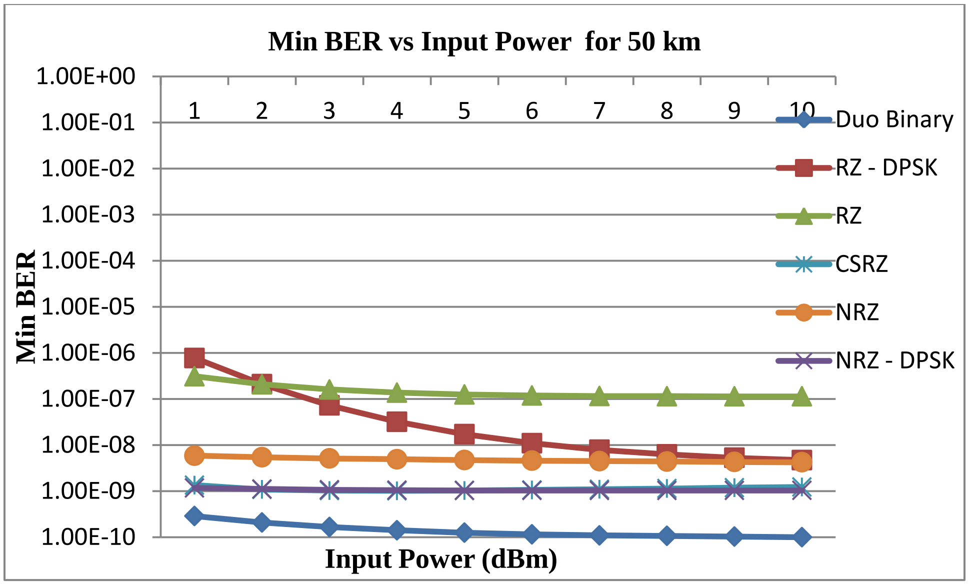

Figure 4. 13 Min BER performance comparison of different modulation formats in terms of input optical power for TWDM-PON with single laser.

Figure 4.13 illustrate Min BER versus launched power. It is observed that Duo binary format has higher Min BER of 1.00E-10 at input power of 10 dBm. CSRZ and NRZ-DPSK also achieves better Min BER of 1.23E-09 and 1.04E-09 for transmission distance of 50 km. In case of RZ-DPSK and RZ performs lower Min BER when they are compared with other modulation formats.

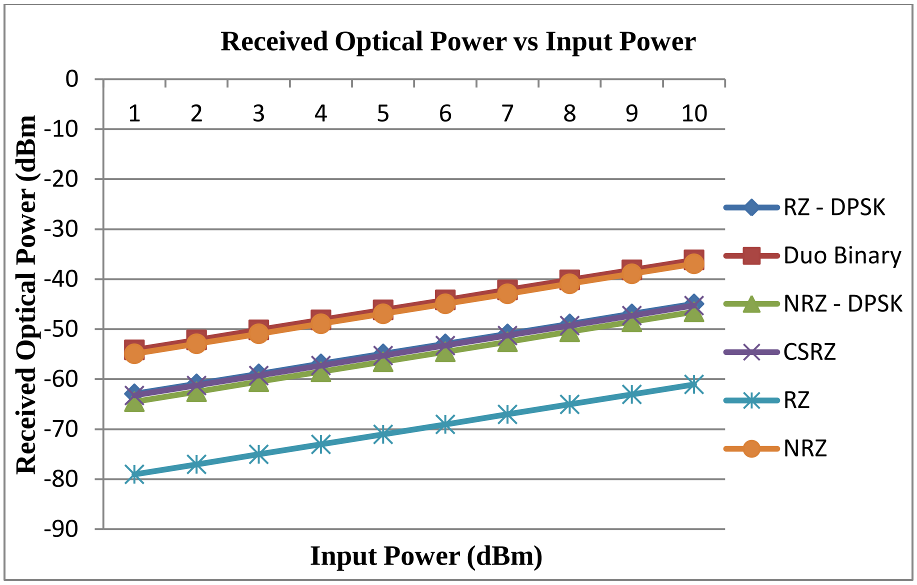

Figure 4. 14 Received optical power performance comparison of different modulation formats for TWDM-PON with single laser

The effect of optical power is analyzed for 50 km transmission distance and it is compared with all the six types of modulation formats. It is shown in the Figure 4.14. Duo binary and NRZ modulation format gives the best performance of Received optical power value of -36.14 dBm and 36.92 dBm respectively, the next good performance is given by NRZ-DPSK and CSRZ of Received optical power value of -46.52 dBm and -45.28 dBm respectively. The least performance of Received optical power is -61.0523 for RZ format at 10 Gbps data rate and 10 dBm input optical power.

4.5 Performance Evaluations of Different Modulation Formats for single laser source of TWDM system using FBG for 100 km.

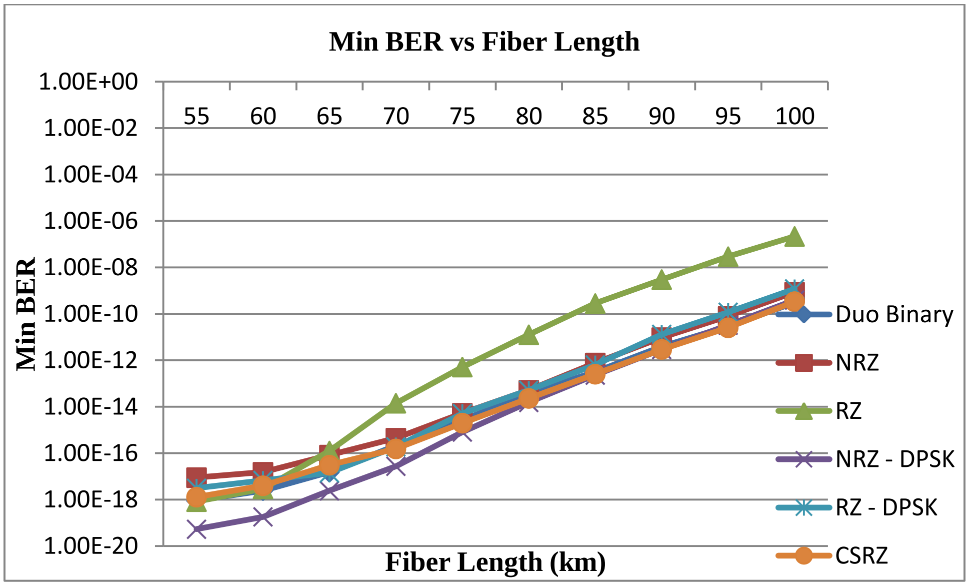

Figure 4.15 Min BER performance comparison of different modulation formats in terms of Fiber length for TWDM-PON with single laser

The effect of distance is analyzed in terms of BER as shown in the Figure 4.15 and it is compared with all the six types of modulation formats for 100 km transmission distance by applying dispersion compensation module of FBG for long transmission. Duo binary and NRZ modulation format gives the best performance of BER value of 3.04E-10 and 8.67E-10 respectively. The next good performance is given by NZR-DPSK and RZ-DPSK of BER value of 3.97E-10 and 1.21E-09 respectively and the least performance showed for RZ format of Min BER of 2.20E-07. At 100 Km distance applying dispersion compensation of FBG the BER value decreases. For the long distance data communication, choosing the optimum BER in Duo binary, NRZ, NRZ-DPSK and RZ-DPSK can be used for optimum distance.

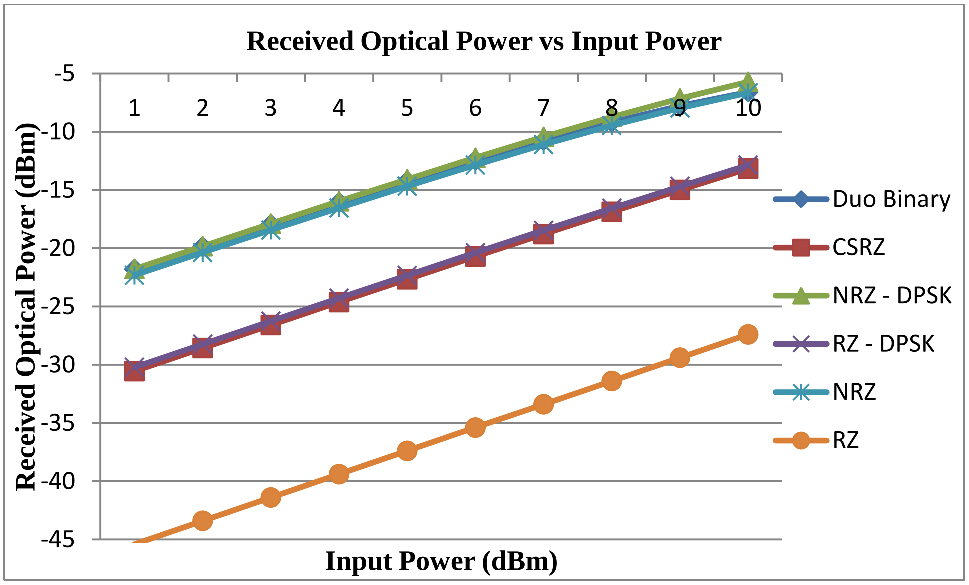

Figure 4.16 Received optical power performance comparison of different modulation formats in terms of input optical power for TWDM-PON with single laser

The Received optical power performance is shown in Figure 4.16 for constant 100 km transmission distance and 10 Gbps data rate by applying FBG. In all modulation formats the Received optical power increases as the input optical power increases due to the power loss during long transmission is compensated as the CW laser power increases. Duo binary and NRZ-DPSK modulation format gives the best performance of Received optical power -6.58233 and -5.70825 respectively. The next good performance is given by RZ-DPSK and CSRZ of Received optical power value of -12.8599 dBm and -13.1567 dBm respectively. Here also RZ modulation formats show lower performance.

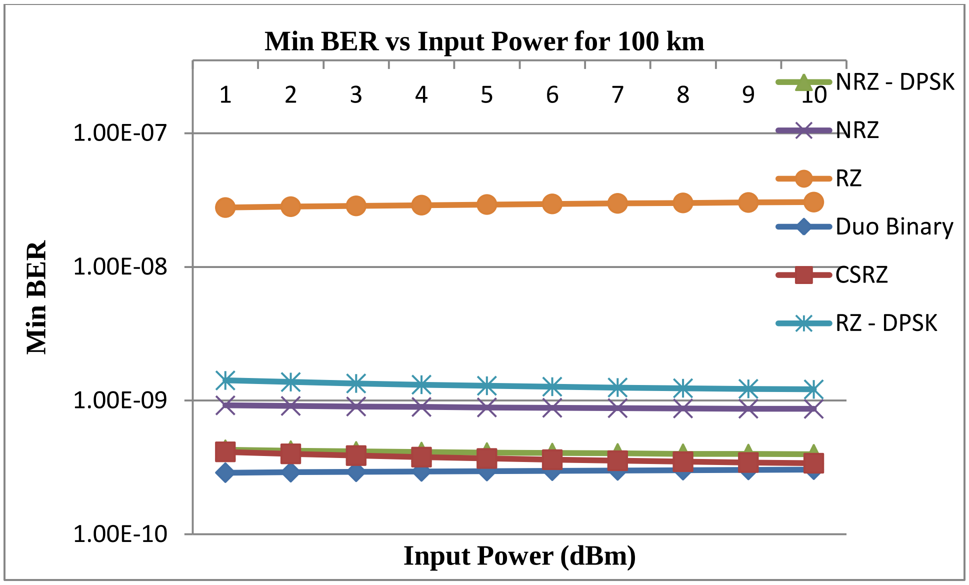

Figure 4.17 Min BER performance comparison of different modulation formats in terms of input optical power for TWDM-PON with single laser for 100 km.

From the result of figure 4.17 we observed that the BER decrease as the input power increases from 0 dBm to 10 dBm. Duo binary, CSRZ and NRZ- DPSK modulation format gives the best performance Min BER than other modulation format.

Table 4.5 Comparison different modulation formats in terms of Min BER, ROP and Q - factor for TWDM-PON with single laser for 100 km

Modulation format	Received optical power (dBm), for 100 km	Q - factor	Min BER
DB	-6.58 dBm	6.84	3.04E-10
NRZ-DPSK	-5.70 dBm	6.12	3.97E-10
CSRZ	-13.15dBm	6.14	3.40E-10
RZ-DPSK	-12.85 dBm	5.94	1.21E-09
NRZ	-6.64 dBm	5.98	8.67E-10
RZ	-27.38 dBm	5.82	2.20E-07

As we can see from Table 4.5 Duo binary performance was better than the performance of CSRZ and NRZ-DPSK although the transmission distance ensured by CSRZ and NRZ-DPSK were longer than the ensured by NRZ, the technical implementation of CSRZ and NRZ-DPSK was considerably more complicated. For single laser source TWDM-PON using FBG for longer transmission considering Duo binary performance was better. On the other hand NRZ is easiest to implement.

4.6 Performance Evaluations of EDFA, RAMAN and SOA for single laser source of TWDM system of 50 km without FBG.

TWDM-PON based on a single laser source OLT is examined using the EDFA, SOA and RAMAN amplifiers on the downstream transmission by considering dispersion effect. This simulation is done by varying transmission distance and input optical power. Where the system is simulated by using pre-defined parameters. In figure shown for different fiber length having a constant signal input power 10 dBm and data rate of 10 Gbps is analyzed.

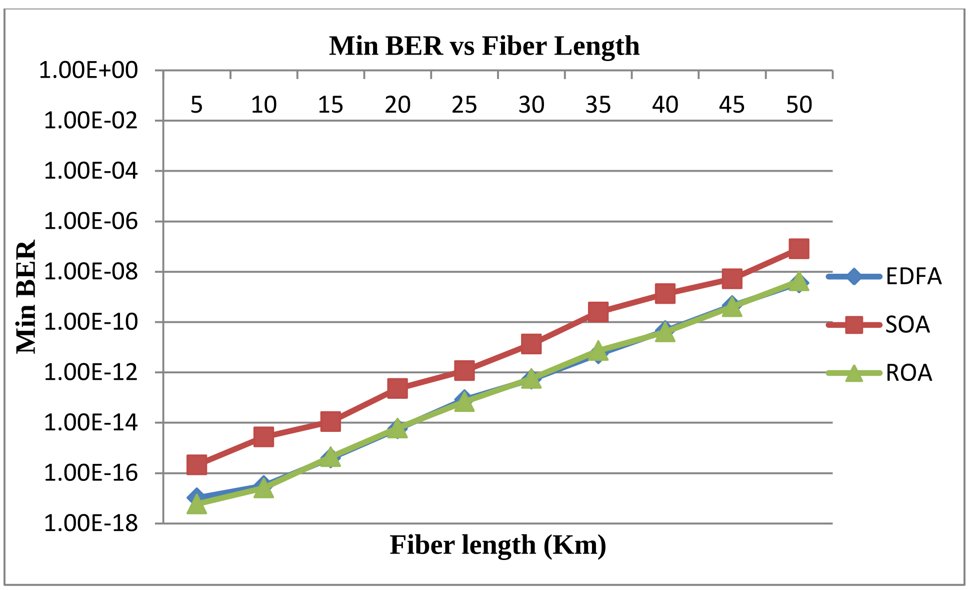

Figure 4.18 Min BER performance comparisons for different optical amplifiers at varying fiber length for TWDM

The Min BER performance is decreased as the transmission distance is increase for all the three amplifiers. It was observed that as the distance was increased up to 10 km, EDFA and RAMAN amplifier showed improved Min BER and provided the best quality of signals, whereas SOA amplifier gave the lower Performance at the same distance. On varying the distance for EDFA from 5 to 50 km, the variation in Min BER was 5.89E-18 to 4.31E-09 with best acceptable value.

Table 4.6 Comparison different Amplifiers in terms of Min BER and Q - factor for TWDM-PON with single laser for 50 km

Optical Amplifiers	Maximum transmission distance with BER of 10^{-10}, km	Q - factor	Min BER
EDFA,	49	6.24	4.50E-10
SOA	45	6.17	2.48E-10
RAMAN	46	6.11	4.04E-10

The Q factor performance also decrease as the fiber length increases, since dispersion and power losses happens with the increment of the transmission distance. At 50 km the Q factor for EDFA was 6.02 whereas, ROA and SOA gives a Q factor value of 5.72 and 5.19 respectively. It was concluded that EDFA amplifier gave better and consistent performance as compared to Raman and SOA amplifiers. Moreover, EDFA provides the maximum transmission distance with a Min of 4.50E-10 and Q factor of 6.24 at 48 km.

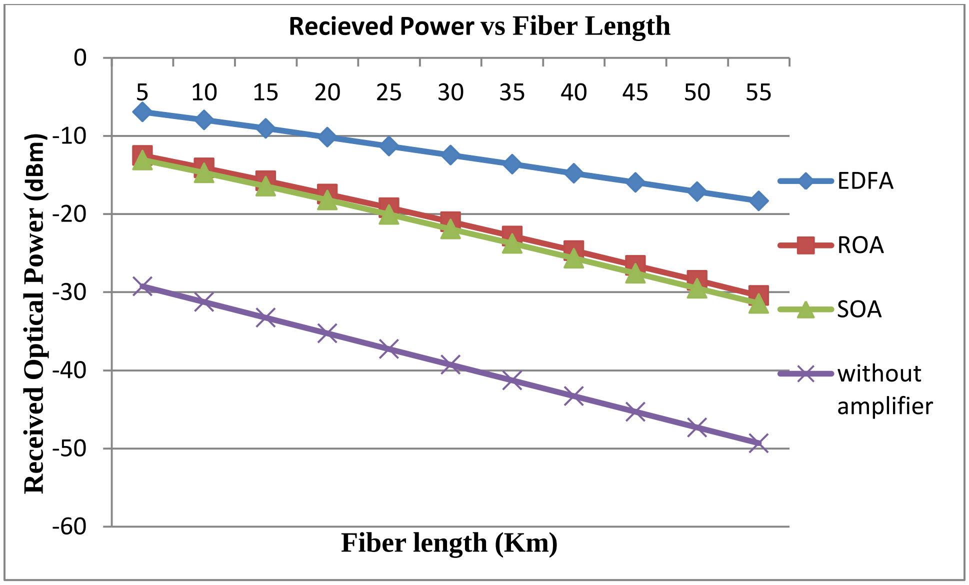

Figure 4.19 Received Optical Power performance comparisons for different optical amplifiers at varying fiber length for TWDM

Figure 4.19 illustrates the graph between BER and transmission distance for different optical amplifiers. It was seen that as the transmission distance increased from 5 to 55 km, there was a decrease in the Received Optical Power for all cases. It can be because nonlinear effete reduced the system's performance. EDFA achieves -18.3056 dBm for 55 km fiber length. While ROA and SOA shows low Received optical power when they are compared with EDFA.

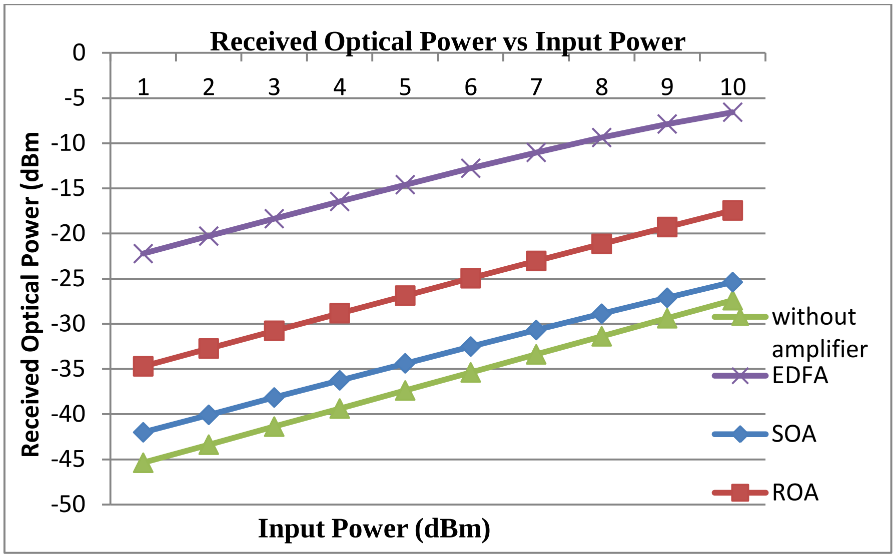

Figure 4.20 Received Optical Power performance comparisons for different optical amplifiers at varying input power for TWDM.

The Received optical power performance for different optical amplifiers is shown in Figure 4.20 for constant 55 km transmission distance and 10 Gbps data rate without applying FBG. By varying CW laser input optical power from 1 dBM to 10 dBm the received signal power is also increased with increasing power. As we can see from the result EDFA amplifier shows best performance of Received Optical Power -6.57312 dBM than the other optical amplifiers. SOA gives lower performance -25.3872 dBM for 50 km length of fiber.

4.7 Performance Evaluations of EDFA, RAMAN and SOA for single laser source of TWDM system considering FBG.

In order to transmit signals over long distances it is necessary to compensate for attenuation losses within the fiber. The performance of various optical amplifiers has been analyzed with transmission distance and transmission power in the terms of Min BER, Received Power and

Quality factor for SOA, EDFA and Raman amplifier. The optical signal is applied to different optical amplifier in order to observe the performance. The Min BER for SOA, EDFA and RAMAN amplifier at 100 km is shown in the Figure

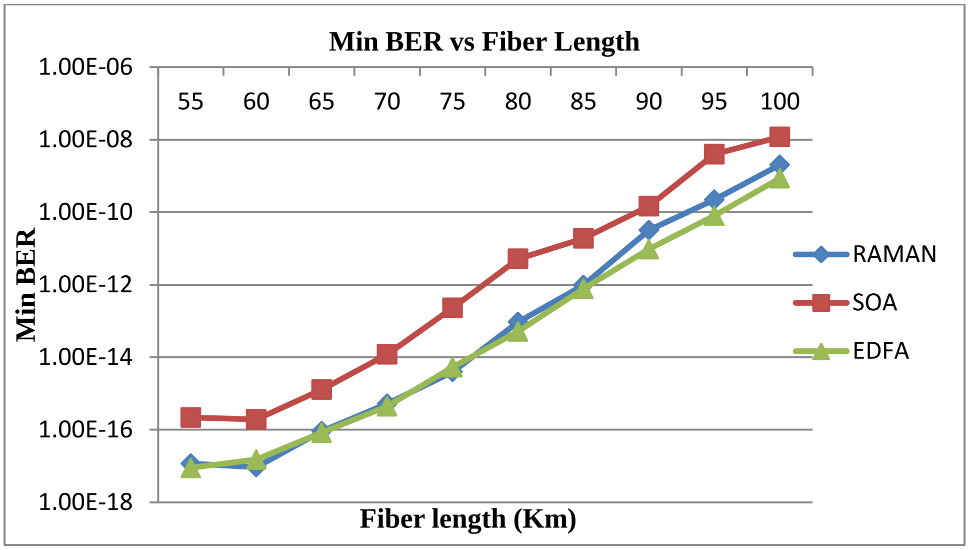

Figure 4.21 Min BER performance comparisons for different optical amplifiers at varying fiber length for TWDM by including FBG.

The Min BER indicates the quality of the received signals, the lower the Min BER, the better will be the communication quality. It was observed that as the distance was increased up to 100 km by keeping the input power of the laser source 10 dBm and the data rate of 10 Gbps. EDFA and RAMAN amplifier showed better Min BER and provided the best quality of signals, whereas SOA amplifier gave low performance at the same distance. The Min BER was 6.67E-10 for EDFA and 2.02E-09 for RAMAN with best acceptable value at 100 km and the SOA Min BER value was 1.19E-08 which is lower than acceptable Min BER for optical communication.

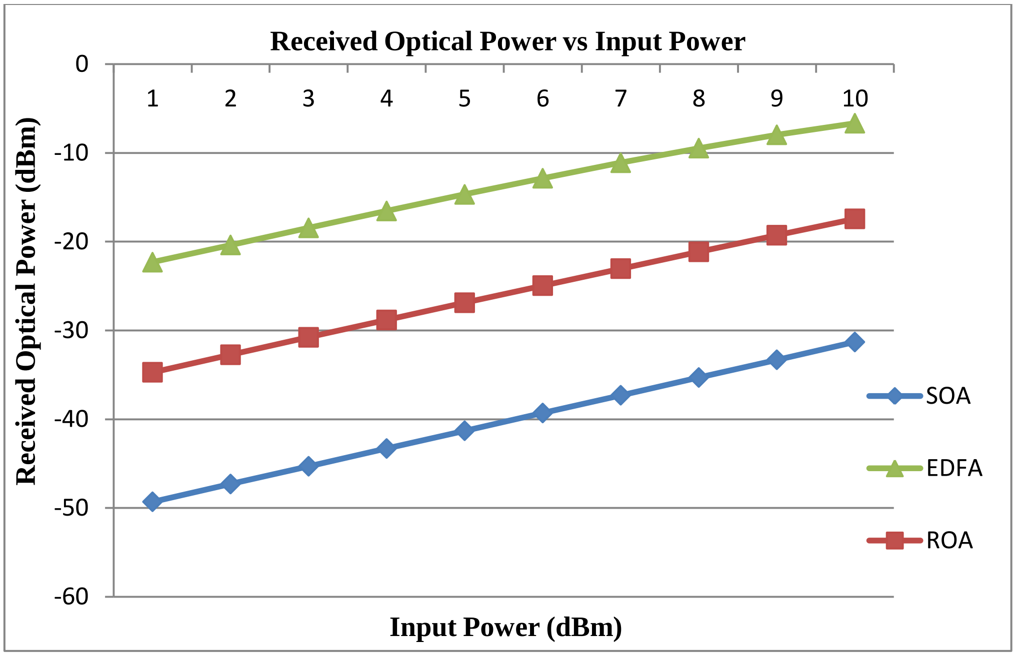

Figure 4.22 Received Optical Power performance comparisons for different optical amplifiers at varying input power for TWDM FBG dispersion compensation.

Figure 4.22 illustrates the graph between Received Optical Power and Input Power for different optical amplifiers. It was seen that as the input optical power of CW laser source increased from 0 dBm to 10 dBm, there was a rise in the Received Optical Power at the ONU. it was observed that EDFA gave the best performance than other optical amplifiers for all input powers. At 100 km transmission distance and input optical power of 10 dBm, Received Optical Power for EDFA was -6.64773 dBm, for the case of Raman was -17.4241 dBm and for SOA was -31.2999 dBm.

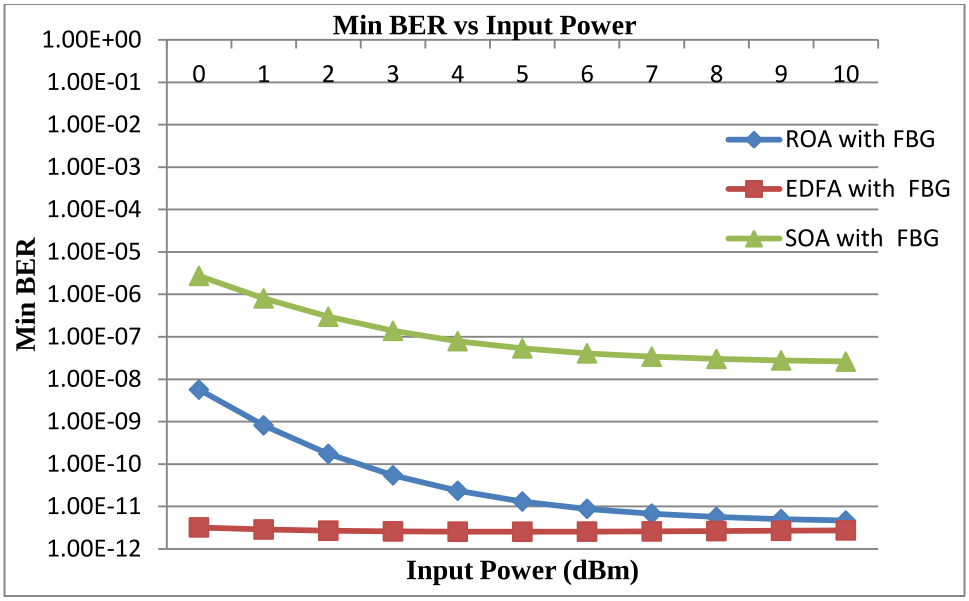

Figure 4.23 Min BER performance comparisons for different optical amplifiers at varying Input Power for TWDM by considering FBG dispersion compensation.

As shown in Figure 4.23, the Min BER decreases with increase in input optical power for different optical amplifiers. SOA and ROA improve Min BER performance as input optical power for a constant length of fiber of 100 km by applying a dispersion compensation module of FGB. The Min BER for all the three amplifiers was at lower transmission distances at 10 dBm input power and EDFA was the one with the highest. ROA and EDFA shows better performance after 8 dBm input optical power while SOA doesn't give min acceptable Min BER at all iterations. Raman and EDFA optical amplifiers can communicate over short distances, while EDFA optical amplifiers can communicate over long distances because of their high gain and low noise.

Table 4.7 comparisons for different optical amplifiers for TWDM by considering FBG dispersion compensation

Single Laser – OLT based TWDM-PON applying OAs	Received Optical Power (dBm) for 100 km using FBG	Received Optical Power (dBm) for 40 km	Received Optical Power (dBm) for achieving 55 km without FBG with min BER of 10^{-9}	Min BER for 45 km Without using FBG	Min BER for 100 km using FBG
EDFA	- 27.53	-14.7721	-18.3056	1.16×10^{-11}	2.72×10^{-12}
ROA	-45.3974	-24.6744	-30.416	1.33×10^{-11}	4.65×10^{-12}
SOA	-44.1127	-25.6429	-31.4322	2.53×10^{-9}	2.60×10^{-9}
Without Amplifier	-62.25	-43.71	-49.3286	1.32×10^{-11}	2.53×10^{-9}

Raman and EDFA optical amplifiers can communicate over short distances, while EDFA optical amplifiers can communicate over long distances because of their high gain and low noise. Raman amplifiers are mainly used in variable wavelength transmission systems with very high capacity where the signal degradation coming from the noise of the EDFAs is not tolerable or the required optical bandwidth is larger then what an EDFA can support. SOA has problems related to line-amplifier polarization sensitivity and relatively high noise figure makes lower performance.

Chapter 5

Conclusion and Future Works

A sine wave with a frequency of 100 GHz from a radio frequency source modulates a single laser source with a wavelength of 1602.31 nm (187.1). The output of the PM modulator produces multi-wavelength signals at seven different wavelengths (186.4 - 187.4 THz) separated by 100 GHz. The multi-wavelength was routed using AWG into separate channels. Four multi-carrier signal which are modulated using different modulation formats signal at frequency of 187 THz, 187.1 THz, 187.2THz, and 187.3 THz for transmission. TWDM-PON using single laser source is designed with input power of 10 dBm for fixed value of transmission distance of 45 km and data rates of 10Gbps for 16 users. It achieves a good Min BER and Q factor performance of 3.80E-10 and 6.11 respectively. It shows almost same performance when we compare with TWDM-PON utilizing four laser source However, improving the TWDM-PON capacity for longer reach is challenging since fiber dispersion imposes several limits on system performance. The performance of six types of modulation formats, NRZ, RZ, NRZ-DPSK, RZ-DPSK, CSRZ and Duo binary has been discussed using Min BER, Q factor, and Received optical signal power as performance metrics. The result shows Duo binary, NRZ and NRZ- DPSK modulation format gives the best performance. In order to TWDM-PON for long-distance communication dispersion compensation is considered in the single laser source design. Also we need optical amplifiers to compensate the power loss since we are using one laser source. By varying the input optical power and fiber length while keeping other parameters constant, the performance of various amplifiers for the designed systems has been evaluated. The results show that the EDFA performs better and increases the transmission distance up to 49 km without dispersion compensation. The transmission distance improved when FBG is used along with EDFA it reaches up to 100 km. performance. In this paper, Duo binary modulation format for pulse generation and EDFA with FBG for compensating power loss and dispersion shows an acceptable Q factor and BER for TWDM-PON using single laser source.

Recommendation for Future Work

In this work TWDM-PON using single laser source for 16 users is designed therefore, we recommended a research could be done for providing more number of users. Additionally Cascaded based amplifier techniques could be investigated to improve performance of optical network communication. We also recommend TWDM-PON using single laser source should done for bidirectional transmission.

Chapter 6

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