Investigation of Wavelength Division Multiplexed Passive Optical Networks

A Dissertation submitted in partial fulfillment of the

requirements for the award of the Degree of

MASTER OF ENGINEERING

IN

ELECTRONICS AND COMMUNICATION ENGINEERING

Submitted By

Komal Preet Kaur

Roll no.: 801161014

Under the Guidance of

Dr. R. S. Kaler

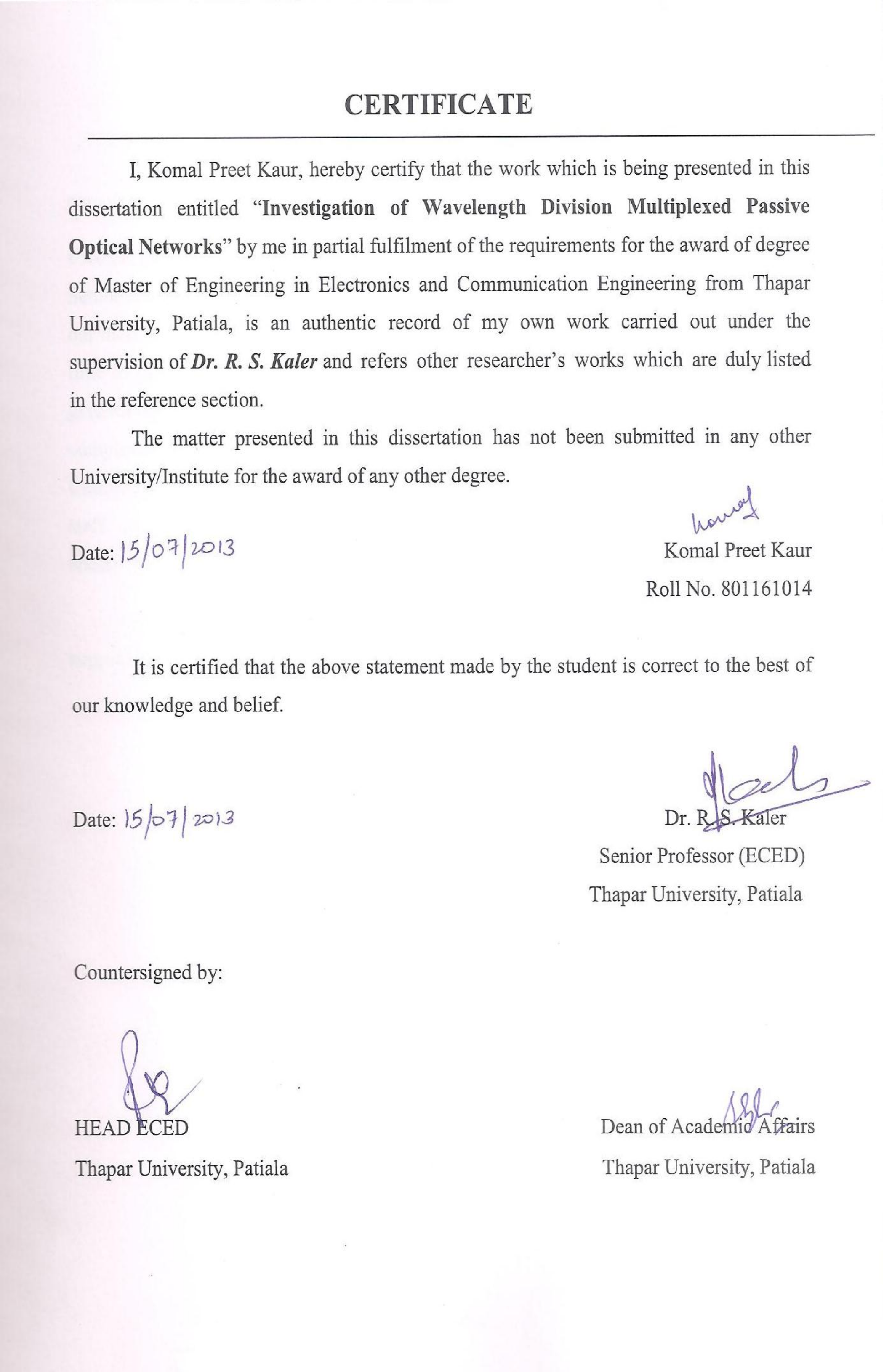
Senior Professor

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

THAPAR UNIVERSITY

(Established under the section 3 of UGC Act, 1956)

PATIALA – 147004 (PUNJAB)



CERTIFICATE

I, Komal Preet Kaur, hereby certify that the work which is being presented in this dissertation entitled "**Investigation of Wavelength Division Multiplexed Passive Optical Networks**" by me in partial fulfilment of the requirements for the award of degree of Master of Engineering in Electronics and Communication Engineering from Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of ***Dr. R. S. Kaler*** and refers other researcher's works which are duly listed in the reference section.

The matter presented in this dissertation has not been submitted in any other University/Institute for the award of any other degree.

komal

Date: 15/07/2013

Komal Preet Kaur
Roll No. 801161014

It is certified that the above statement made by the student is correct to the best of our knowledge and belief.

Date: 15/07/2013

Dr. R. S. Kaler
Senior Professor (ECED)
Thapar University, Patiala

Countersigned by:

HEAD ECED
Thapar University, Patiala

Dean of Academic Affairs
Thapar University, Patiala

ACKNOWLEDGEMENT

All praises to almighty WAHEGURU who give me strength and abilities to complete this thesis work successfully.

I would like to give my sincere gratitude to my honourable supervisor **Dr. R. S. Kaler**, Senior Professor ECED, for his assistance and good guidance time after time which made our thesis work become more precise and attractive. He supervises me and gives his spare time to discuss more about the problem of dissertation work. At the same time, I am grateful to Head of Department, **Dr. Rajesh Khanna** for providing the facility for completion of dissertation. I convey my sincere thanks to **Dr. Kulbir Singh,** P.G Coordinator Electronics and Communication Engineering Department, entire faculty and staff of Electronics and Communication Department at Thapar University for the encouragement and cooperation.

I am grateful to my beloved parents and friends for their love and continuous support during the dissertation work at Thapar University until finish.

Komal Preet Kaur
Roll No. 801161014

ABSTRACT

The fastest growing areas in telecom are broadband services and networks. The explosion of the Internet coupled with new video centric services has increased the demand for high bandwidth in access networks. Fiber to the home, based on a PON due to its high bandwidth, cost sharing of infrastructure, and absence of active components, is considered as a good solution to this demand. Services such as IP high-definition video delivery, Voice-over-IP, social networking and cloud computing have pushed the demand for bandwidth even beyond what is achievable with today's gigabit PONs. WDM-PON is a promising candidate of the low-cost subscriber networks for the fiber-to-the-home systems. Its upgradability, large capacity and flexibility are its qualities that make it such a promising candidate. Wavelength-division-multiplexing transmits multiple data signals using different wavelengths of light through a single fiber. The objective of this dissertation is to investigate and propose low cost architectures for high speed performance of Passive Optical Network.

Firstly, an 80 km ring based WDM-PON architecture for high speed data communication is proposed. In this ring architecture the data is transmitted at a rate of 4×12 Gb/s at each node. Secondly, the performance effect of WDM PON architecture is analyzed using different receiver filters. The results obtained with Bessel filter are the best amongst the other filter results. Thirdly, a low cost architecture to integrate multiple PONs to a long reach spectrum sliced WDM network is proposed. LEDs are used as a broadband light source.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

List of Abbreviations

CO	Central Office
OLT	Optical Line Terminal
WDM	Wavelength Division Multiplexing
OADM	Optical Add Drop Multiplexer
WDM-PON	Wavelength-Division-Multiplexed Passive Optical Network
SMF	Single Mode Fiber
DCF	Dispersion Compensating Fiber
NZDSF	no-zero dispersion shifted fiber
VPN	Virtual Private network
ASE	Amplified Spontaneous emission
FBG	Fiber Bragg Grating
FP-LD	Fabry–Pérot laser diodes
SLD	Superluminescent Diode
RSOA	Reflective Semiconductor Optical Amplifier
FWM	Four Wave Mixing
EDFA	Erbium-Doped Fiber Amplifiers
DSF	Dispersion Shifted Fiber
SOA	Semiconductor Optical Amplifier
NRZ-DPSK	Non-Return To Zero Differential Phase Shift Keying
NRZ	Non-return to zero
MZM	Mach-Zehnder Modulator
ONU	Optical Network Units
ITU	International Telecommunication Union
TDM	Time-Division Multiplexed
NG	New generation
SS WDM-PON	Spectrum Sliced WDM-PON
BER	Bit Error Rate
Q- factor	Quality Factor
OSRNR	Optical-Signal-To-Rayleigh-Noise-Ratio
RN	Remote Node

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION:

The rapid expansion of high-speed internet market and data communications has accelerated the demand for broadband access [1]. Broadband services and networks are among the fastest growing areas in telecom. The demand for greater bandwidth in access is already fuelling a similar growth in all remaining part of the networks and will continue to do so even more. Assuming the existing technology, such bandwidth growth implies a profitability dilemma for operators, as network costs grow quicker than revenues: new services span many more orders of magnitude in terms of bandwidth requirements which cannot be matched by any old-style tariffs policy nor supported by the existing network approach. There is a compelling need to deliver new services to a wide number of users over a unique platform while achieving convergence (a network for all the services), flexibility (a network for every situation) and lowering overall costs (low investment and maintenance cost). The only sensible way to reduce the costs of ownership while delivering high bandwidth services is to use a very simple network, capable to fully exploit the benefit of the optical technology and fiber based networks [2]. The explosion of the Internet coupled with new video centric services has increased the demand for high bandwidth in access networks [3]. Fiber to the home, based on a passive optical network (PON), has been extensively investigated due to its high bandwidth, cost sharing of infrastructure, and absence of active components [4, 5]. Historically, the maximum transmission length of a PON has been considered to be 20 km. Gigabit PONs are being widely deployed in response to the exploding demand for high bandwidth [6]. Services such as IP high-definition video delivery, voice-over-IP (VoIP), social networking and cloud computing will push the demand for bandwidth even beyond what is achievable with today’s gigabit PONs [7-9]. However, these types of optical access networks which typically serve 32 customers over reaches ranging from 20 km to 60 km (in the case of reach extended PONs) may not be the ultimate solution for network operators which seek to radically reduce the cost of supplying broadband services [10]. In next generation, the wide-area broadband access networks are required to offer high-speed connection services between the central office (CO) and Remote Nodes (RNs). The wavelength-division-multiplexed passive optical network (WDM-PON) is a promising candidate of the low-cost subscriber networks for the fiber-to-the-home systems due to its large capacity and flexibility [11]. Passive optical networks (PONs) such as gigabit Ethernet PONs and gigabit-capable PONs are being deployed in several countries. These systems provide users with a wide bandwidth, but it is necessary to prepare a migration path that allows the service bandwidth of working systems to be upgraded. Several migration scenarios using wavelength-division multiplexing (WDM) have been reported recently [12]. In these papers, a smooth migration from existing PONs to WDM-PONs is achieved by overlaying the WDM-PON on the deployed systems. To achieve coexistence between the WDM-PON and the existing systems, the wavelength band assigned to the WDM-PON is limited to over 1500 nm. To establish bandwidth-guaranteed services for many users by assigning dedicated wavelengths to each user, dense WDM (DWDM) technology is required [13]. Dense wavelength-division-multiplexed (DWDM) passive optical networks (PONs) offer a potentially cost-effective way of increasing individual customer bandwidths through increased use of the wavelength domain [14].

1.2 BACKGROUND:

The early 1990s saw a second generation of WDM, sometimes called narrowband WDM, in which two to eight channels were used. These channels were spaced at an interval of about 400 GHz in the 1550-nm window. By the mid-1990s, dense WDM (DWDM) systems were emerging with 16 to 40 channels and spacing from 100 to 200 GHz. By the late 1990s DWDM systems had evolved to the point where they were capable of 64 to 160 parallel channels, densely packed at 50 or even 25 GHz intervals. The progression of the technology can be seen as an increase in the number of wavelengths accompanied by a decrease in the spacing of the wavelengths. Along with increased density of wavelengths, systems also advanced in their flexibility of configuration, through add drop functions, and management capabilities. Increases in channel density resulting from DWDM technology have had a dramatic impact on the carrying capacity of fiber [15].

Passive optical networks are a key technology to enable the development of an optical access network. Currently there are many versions of PON technology [16]. First developed in the 1980s the technology was furthered with the development of the Broadband PON to carry broadband data over 20 km to 32 customers at symmetrical data rates of up to 622 Mb/s. The IEEE has also developed a PON architecture as part of the Ethernet in the First Mile project. Ethernet-PON (EPON) are capable of delivering Ethernet encapsulated data at a rate of 1 Gb/s symmetrical with commercially available systems demonstrating 64 users over a range of up to 20 km [16]. However, the highest capacity standardized PON architecture is the Gigabit- PON standardized by the ITU-T, which is capable of operating at 2.5 Gb/s symmetrical data rates, connecting up to 64 customers over 20 km [17]. The next generation PON techniques were integrated with WDM technique to increase the capacity. Subsequent to the current generation WDM-PON, the next generation PON techniques will be integrated with DWDM technique to further increase the capacity.

1.3 MOTIVATION:

There are many promising features which make WDM-PON a popular technology for next generation [15, 18]

- From both technical and economic perspectives, the ability to provide potentially unlimited transmission capacity is the most obvious advantage of DWDM technology
- Because WDM is a physical layer architecture, it can transparently support both TDM and data formats such as ATM, Gigabit Ethernet, ESCON, and Fiber Channel with open interfaces over a common physical layer.
- Fast, simple, and dynamic provisioning of network connections give providers the ability to provide high-bandwidth services in days rather than months.
- PONs allow for long reach between the CO and customer premises, operating at distances up to 20 km
- PONs minimize fiber deployment in both the CO and the local loop.
- PONs provide higher bandwidth due to deeper fiber penetration, offering Gb/s solutions.
- Operating in the downstream as a broadcast network, PONs allow for video broadcasting either as IP video, or analog video.
- PONs eliminate the necessity of installing active multiplexers at the splitting locations, thus relieving network operators from the task of maintaining active curbside units and providing power to them.

- Being optically transparent end-to-end, PONs allow upgrades to higher bit rates or additional wavelengths.

1.4 OPTICAL NETWORKING:

An optical network connects computers (or any other device which can generate or store data in electronic form) using optical fibers. To facilitate data communication, an optical network also includes other optical devices to generate optical (electrical) signals from electrical (respectively optical) data, to restore optical signals after it propagates through fibers, and to route optical signals through the network. Basically optical networks are those in which the dominant physical layer technology for transport is optical fiber. They can be opaque or all-optical, and can be single-wavelength or based on dense wavelength division multiplexing (DWDM).

Optical fiber networks are used because of their potentially limitless capabilities, as follows [19]:

- huge bandwidth (over 50 terabits per second (Tbps),
- low signal attenuation (as low as 0.2 dB/km), so repeater-less transmission over long distances is possible,
- immunity to electromagnetic interference,
- high security of signal because of no electromagnetic radiation, so difficult to eavesdrop,
- no crosstalk and interferences between fibers in the same cable,
- low signal distortion, suitable for carrying digital information,
- low power requirement,
- low material usage, small space requirement, light weight, non-flammable, cost-effective
- high electrical resistance, so safe to use near high-voltage equipment or between areas with different earth potentials.

1.5 WAVELENGTH DIVISION MULTIPLEXING:

In order to exploit the fiber's huge bandwidth we introduce concurrency among multiple user transmissions into the network architectures and protocols. In an optical communication network, this concurrency may be provided according to either wavelength or frequency (wavelength-division multiplexing (WDM)), time slots (time division multiplexing (TDM)), or wave shape (spread spectrum, code-division multiplexing (CDM)).

Under (optical) TDM, each end-user should be able to synchronize to within one time slot. The optical TDM bit rate is the aggregate rate over all TDM channels in the system. In CDM the optical CDM chip rate may be much higher than each user’s data rate. As a result, both the TDM bit rate and the CDM chip rate may be much higher than electronic processing speed, i.e., some part of an end user's network interface must operate at a rate higher than electronic speed. Thus, TDM and CDM are relatively less attractive than WDM, since WDM - unlike TDM or CDM - has no such requirement. Specifically, WDM is the favorite multiplexing technology for practical optical communication networks since all of the end-user equipment needs to operate only at the bit rate of a WDM channel, which can be chosen arbitrarily, e.g., peak electronic processing speed.

Under WDM, the optical transmission spectrum is carved up into a number of non-overlapping wavelength (or frequency) bands, with each wavelength supporting a single communication channel operating at whatever rate one desires, e.g., peak electronic speed. Thus, by allowing multiple WDM channels to coexist on a single fiber, one can tap into the huge fiber bandwidth, with the corresponding challenges being the design and development of appropriate network architectures, protocols, and algorithms.

WDM transmits multiple data signals using different wavelengths of light through a single fiber. Incoming optical signals are assigned to specific frequencies within a designated frequency band. Multiple channels of information carried over the same fiber, each using an individual wavelength [18].

DWDM is a WDM with closely spaced channels. The channel spacing is reduced upto 0.8nm (i.e 100 GHz) or even less. Currently the work is being done upon 0.2nm (25GHz) or 0.1 nm (12.5 GHz). DWDM spaces the wavelengths more closely than does WDM, and therefore has a greater overall capacity [15].

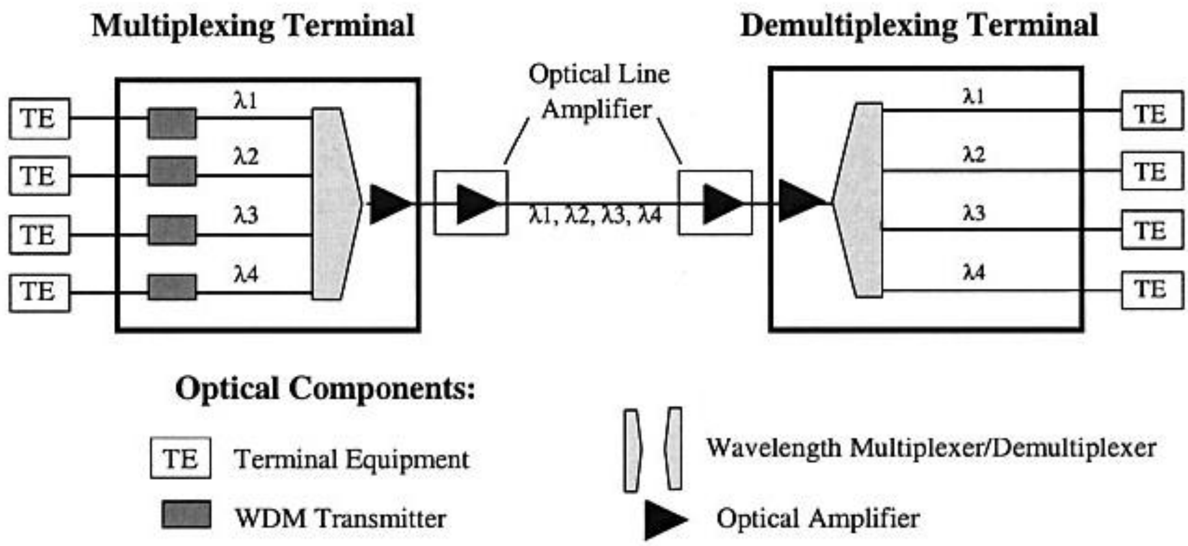


Figure 1.1 Four-Channel Point-To-Point WDM Transmission System [18]

The system performs the following main functions:

- Generating the signal—The source, a solid-state laser, must provide stable light within a specific, narrow bandwidth that carries the digital data, modulated as an analog signal.
- Combining the signals—Modern DWDM systems employ multiplexers to combine the signals. There is some inherent loss associated with multiplexing and demultiplexing. This loss is dependent upon the number of channels but can be mitigated with optical amplifiers, which boost all the wavelengths at once without electrical conversion.
- Transmitting the signals—The effects of crosstalk and optical signal degradation or loss must be reckoned with in fiber optic transmission. These effects can be minimized by controlling variables such as channel spacing, wavelength tolerance, and laser power levels. Over a transmission link, the signal may need to be optically amplified.
- Separating the received signals—at the receiving end, the multiplexed signals must be separated out. Although this task would appear to be simply the opposite of combining the signals, it is actually more technically difficult.
- Receiving the signals—the demultiplexed signal is received by a photodetector.

In addition to these functions, a DWDM system must also be equipped with client-side interfaces to receive the input signal. This function is performed by transponders. On the DWDM side are interfaces to the optical fiber that links DWDM systems.

1.6 PASSIVE OPTICAL NETWORKS:

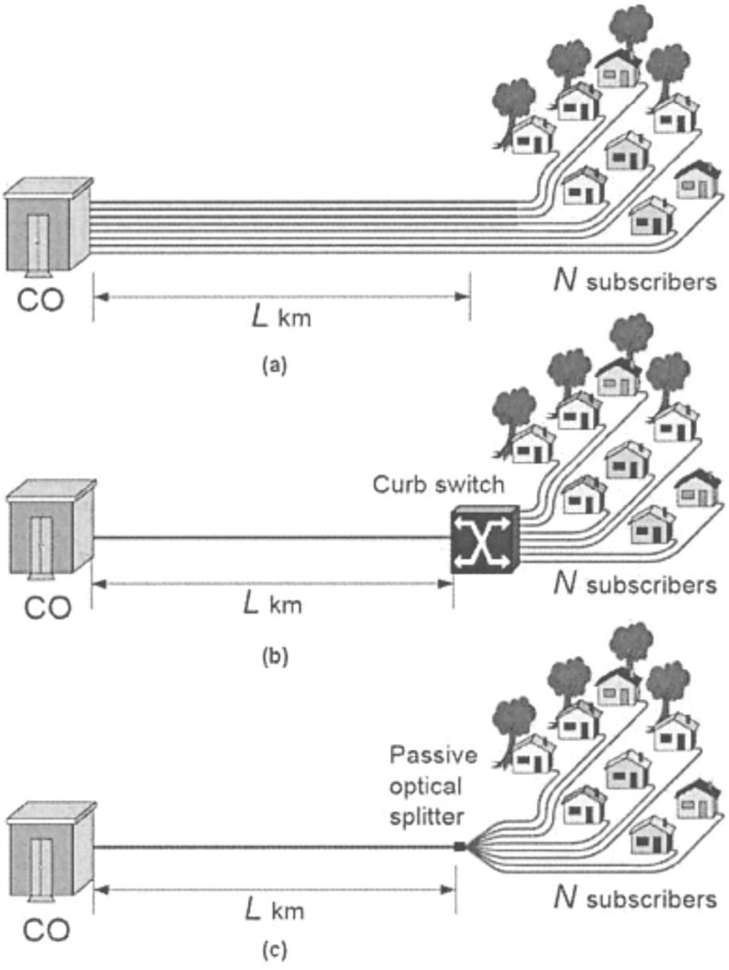


Figure 1.2 Fiber-to-the-home (FTTH) deployment scenarios [18]

Fiber-to-the-home (FTTH) is the technology that supports the upcoming interactive multimedia services & can be implemented on a point-to-point basis where a dedicated fiber pair is used to connect each customer's Optical Network Terminal (ONT) to the Optical Line Termination (OLT) at the CO. This requires the installation of a large amount of fiber cable and can lead to large costs for power, thermal, and interconnect management [20, 21]. A more efficient approach is to use a shared fiber connecting the OLT to a group of customers through a RN. The user ONTs are connected to the RN with dedicated fiber cables of much shorter length. Active routing equipment could be placed at the RN, but these results in increased powering and maintenance cost. To alleviate these costs, passive equipment can be used at the RN, in which case the network architecture is referred to as a PON. In these the optical signal is switched through passive splitters. In these types of special splitters, the signal from the CO is transmitted to number of users without any need of power signal [22]. Also, these networks require only N+1 optical transceivers i.e. minimum number of transceivers and there is no need of electro-optical conversion.

All transmissions in a PON are performed between an Optical Line Terrninal (OLT) and Optical Network Units (ONUs) (Figure 1.3). The OLT resides in the CO and connects the optical access network to the metropolitan area network (MAN) or wide-area network (WAN), which is also known as backbone or long-haul network. The ONU is located either at the end-user location (FTTH and FTTB), or at the curb, resulting in fiber-to-the-curb (FTTC) architecture.

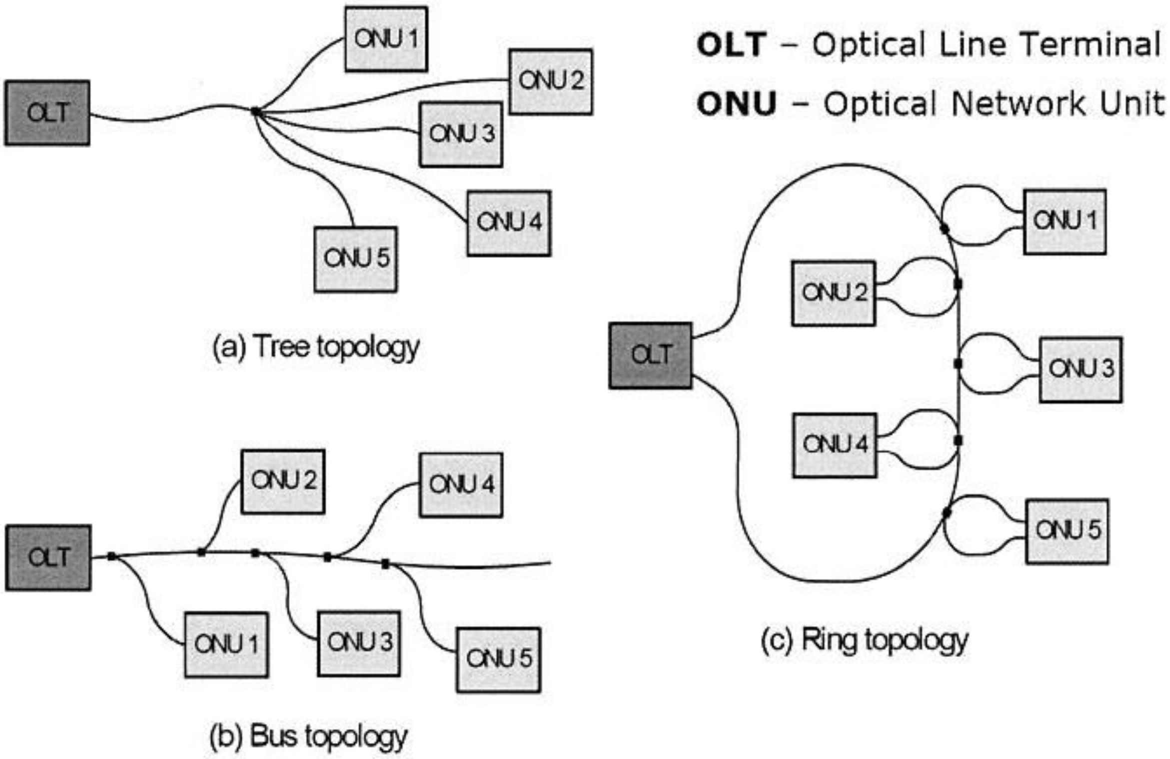


Figure 1.3 PON Topologies [18]

1.7 WAVELENGTH DIVISION MULTIPLEXED PASSIVE OPTICAL NETWORKS:

Although the PON is a significant step towards providing broadband access to the end user, it is not very scalable. Since the basic form of PON emlploys only a single optical channel, the available bandwidth is limited to the maximum bit rate of an optical transceiver, which, under current technologies is, 1 Gbps. The attenuation due to splitting limits the maximum number of ONUS to 64. This limits the network's scalability. The deployment cost of laying fiber in the access network being high, it is important to consider technologies which may help scale the PON capacity in future.

Many telecom operators are considering to deploy PONs using a Fiber-to-the-x (FTTx) model to support converged Internet Protocol (IP) video, voice, and data services - defined as "triple-play" - at a cheaper subscription cost than the cumulative of the above services deployed separately [23]. Although the PON provides higher bandwidth than traditional copper-based access networks, there exists the need for further increasing the bandwidth of the PON by employing Wavelength-Division Multiplexing (WDM) so that multiple wavelengths may be supported in either or both upstream and downstream directions. Such a PON is known as a WDM-PON [23]. A WDM-PON is a point-to-point access network (as opposed to point-to-multipoint in PON), in which there exists a separate wavelength, between the OLT and each ONU.

Each wavelength is routed by a passive Arrayed Waveguide Grating (AWG). In a WDM-PON, different ONUs can be supported at different bit rates, if necessary. Each ONU can operate at a rate up to the full bit rate of a wavelength channel; therefore, it does not have to share the available bandwidth with any other ONU in the network. Moreover, unlike the basic PON, the WDM-PON does not suffer power-splitting losses. Use of individual wavelengths for each ONU also facilitates privacy and reduces security concerns which the PON has. Finally, because of the periodic routing pattern of a AWG, the WDM-PON is easily scalable. Keeping in view such advantages that WDM-PONS have, WDM was recommended as an upgrade to the PON in the ITU-T G.983 [24].

A hybrid dense-wavelength-division-multiplexing (DWDM) system can fully utilize the fiber bandwidth and increase the transmission capacity of a fiber link. It uses different optical channels to carry combined OC-48 (2.5 Gbps) digital baseband and AM-VSB analog video signals, for example, would be quite useful for a fiber transport network providing both telecommunication and CATV services [25],[26]. The PON is a promising approach to obtain low cost optical access. DWDM in combination with PON has received considerable attention in many fields, it is the most promising candidate for light wave transport system due to its large capacity, network security, easy management, and upgrade-ability [27-29].

1.8 OBJECTIVE OF DISSERTATION

1. To propose architecture for high speed performance of Passive Optical Network.
2. To investigate the performance effect of a Wavelength Division Multiplexed Passive Optical Network.
3. To propose a cost effective architecture for optimized performance of Passive Optical Network.

1.9 ORGANIZATION OF DISSERTATION

Chapter 2 gives literature survey about the topic of the dissertation. In order to start the dissertation, the first step is to study the papers that have been already published by other researchers. Paper related to this work are chosen and studied. With the help of literature review, it becomes easier to perform this work.

Chapter 3 presents a ring based WDM-PON architecture for high speed data communications.

Chapter 4 explains performance analysis of WDM-PON architecture using different receiver filters

Chapter 5 presents a low cost architecture to integrate multiple PONs to a long reach spectrum sliced WDM network
Chapter 6 includes the Conclusion and Future Prospect of the work.

CHAPTER 2

LITERATURE SURVEY

Darren P Shea and John E Mitchell [17] demonstrated the feasibility of an architecture that consolidates a number of deployed PON infrastructures into a long-reach, high-split ratio system which further increases equipment sharing between users. The demonstrated system allows the use of uncooled lasers with possible wavelength drift across a CWDM band (20 nm) with optical amplification and narrow optical filtering with no performance degradation. A complete study of potential implementations was performed with experimental results showing that a target performance of 10−10 could be achieved over 120 km of standard fiber with transmitter wavelengths from 1542 to 1558 nm and DWDM backhaul wavelengths from 1520 to 1535 nm.
R.S Kaler *et.al*. [30] demonstrated that in case of SMF the second and third order dispersion has minimum impact on intensity and frequency on optical system..
Kyeong Soo Kim *et al.* [31] compared the current PON based FTTH solutions, ATM-PON (APON), Ethernet PON (EPON) and provided a possible evolution scenario to future WDM PON. Once fibers are deployed with PON based FTTH solutions, it becomes critical migrating to WDM PON from Time Division Multiplexing (TDM) used in current PON solutions.

Fu-Tai An *et al.* [32] investigated the key issues and reviewed enabling technologies for upgrading current generation optical access networks with WDM techniques. It is studied that upgrading crrent generation TDM based optical access networks will be a challenge in the future when end user demand outgrows current network capacity.

Samir Chatterjee *et al.* [33] studied global infrastructures that are beginning to emerge and host of broadband services appear and deliver economical service to users at offices and homes; optical networking will become serious candidate for widespread implementation.

B. Chen, C. Gan [34] in 2011 demonstrated and presented WDM-PON based on a central single-fiber ring and secondary trees. With the proposed architecture, both protection and dynamic wavelength assignment can be realized. The central ring can provide protection for the feeder fiber. The design of the RN can realize the function of dynamic wavelength assignment. This architecture is designed mainly for large-scale networks in the next generation. The concept of CO design balances the load of the system, reduces the power budget and provides protection in case of a fiber cut. The design of the RN makes it possible to realize the function of protection under the condition that the components are unidirectional. The use of WB in the RN makes it possible to drop wavelength at RN dynamically. The feasibility of the proposed architecture has been evaluated by simulation results of the system performances.

H. Suzuki *et al.* [35] proposed and developed an advanced dense wavelength division multiplexing small form factor pluggable (DWDM-SFP) transceiver for the L-band, which features a wavelength tunability of 3 nm. By using the developed wavelength-tunable DWDM-SFP transceiver, a colorless optical network unit (ONU) prototype for coexistence-type wavelength division multiplexing passive optical networks (WDM-PONs) that enable coexistence with existing PONs is achieved. Both wavelength and temperature dependencies of the colorless ONU prototype are evaluated and the applicability to the existing Class B+ optical distribution network that has a 28 dB loss is discussed in this paper.

S. M. Lee *et al.* [36] demonstrate a bidirectional long-reach 64-channel dense wavelength division multiplexing passive optical network (DWDM-PON) based on wavelength-locked Fabry–Pérot laser diodes (F–P LDs) with 50-GHz channel spacing. The mode control of the F–P LDs enhances the output power and decreases the required injection power. Packet-loss-free transmission in both 64 upstream and 64 downstream channels is obtained, guaranteeing more than 100 Mb/s per channel through 70 km of single mode fiber without the need for an optical amplifier. The demonstrated DWDM-PON can consolidate a metro network into an access network by bypassing the central offices within its reach. The long-reach DWDMPON can also accommodate 80 subscribers (10-Gb/s capacity for both upstream and downstream) with an EDFA-based BLS. A further expansion of subscribers (capacity) is possible with a semiconductor-based BLS with a wider bandwidth.

C. W. Chow *et al.*[37] proposed a novel scheme for reducing Rayleigh beat noise in centralized light source dense wavelength-division-multiplexed passive optical networks is demonstrated using an optimized channel-detuned optical filtering of 30 GHz and phase-modulation-induced spectral broadening of a 10-Gb/s upstream nonreturn-to-zero signal. The required optical-signal-to-Rayleigh-noise-ratio (OSRNR), characterized experimentally, can be reduced by up to 16 dB while retaining negligible transmission penalty over 20-km single-mode fiber without dispersion compensation. Numerical analysis is performed to study the tradeoff between OSRNR improvement and attenuation of the PM-NRZ signal as a function of different channel detuning and center wavelength suppressions.

F. Payoux *et al.*[38] demonstrated the feasibility of a polarisation insensitive bidirectional WDM PON based on the spectrum slicing of a single SLED shared between all users and remodulation at the ONU with a RSOA for upstream. They have achieved 1.25 GbiUs per user upstream over 20 km for 40 users. This single-fibre architecture is particularly interesting because of the low cost components used in polarisation insensitive colorless ONUs with high bandwidth capabilities.

K. Iwatsuki *et al.*[39] describes in hi paper the technical issues of access and metro networks based on wavelength division multiplexing(WDM) technologies, some solutions, and an experimental demonstration. A WDM star access network with colorless optical network units (ONUs) is proposed. For realizing the colorless ONU, two approaches are introduced; optical carrier supply and spectrum slicing. In addition, a WDM metro ring network with scalable optical add/drop multiplexers (OADMs), namely the tapped-type OADM, is proposed to effectively accommodate the large amount of traffic issued from access networks. It was also shown that the network based on the spectrum slicing scheme supported 10-km access lines with under 20-dB loss; 125-Mb/s upstream and 1.25-Gb/s downstream bandwidths were offered to each of 8 users. In WDM metro networks, the technical issues are how to realize significant scalability and low start-up-cost. As the solution, they proposed the tapped-type OADM using an OCSM that is a scalable WDM light source based on multicarrier generation. By connecting a CN and four tapped-type OADMs including OCSMs, it was shown that a 12.5-GHz-spaced, 200-km DWDM metro ring network with the span loss of 15 dB (40 km) can be constructed; it offers 1.25-Gb/s upstream and 1.25-Gb/s downstream bandwidth per wavelength. These experiments utilizing prototypes confirmed the feasibility of the proposed WDM technologies for both access and metro networks.

A. R. S. P. Shirazi *et al.*[40] analysed the behaviour of the SOAs in the optical networks and then they proposed a numerical simple model to simulate the behaviour of the semiconductor optical amplifiers. After that by employing this model as inline amplifier for a DWDM optical system, we have simulated the transmission of 10 channels with bit rate 10 Gb/s up to distance

3970 km with RZ-DPSK modulation format at 20 GHz channel spacing. On the other hand in order to amplify the signal at the transmission link, they have used 73.5km relay span consist of 63km single mode fiber (SMF), 10.5km dispersion compensating fiber (DCF) and a SOA at the end. Our results show that by optimizing the key parameters of the SOA such as the bias current and the input power and furthermore by proper placement of the spans, signal can be transmitted with good amplification and low noise power up to distance 3970 km.

L. Deng *et al.*[41] proposed a novel WDM-PON architecture to support efficient and bandwidth-scalable virtual private network (VPN) emulation over both inter-PON and intra-PON. The virtual ring link for the VPN communications among ONUs is realized by using additionally low-cost optical passive components and OFDMA technology. Moreover, the downstream traffic wavelength is reused for the upstream traffic signal by using re-modulation technology. In this paper they present a report on a successful transmission of 10.7 Gbps OOK upstream and 10.7 Gbps DPSK downstream, together with 1.25 Gbps 16-QAM OFDM VPN traffic, over 20 km no-zero dispersion shifted fiber (NZDSF). The performance of upstream transmission is deteriorated by 4.5 dB caused by Rayleigh backscattering noise and PM-to-IM noise. Furthermore, 1.25 Gbps 16-QAM OFDM VPN traffic is also tested for both inter-PON and intra-PON cases. The proposed system provides a feasible and promising solution to achieve broadband VPN emulation over multi-WDM-PON systems for next generation optical access networks.

U. H. Hong *et al.*[42] proposed a novel multi-ring architecture that can be used to implement a self-protected WDM PON cost-effectively. To improve the scalability of this network, they implemented several sub-rings within the main ring by using a few extra fiber connections between the RN and several ONUs. For a demonstration, they implemented bidirectional ONUs with a pass loss of 3 dB. Thus, they could install up to 6 ONUs in a sub-ring. Using these ONUs, they evaluated the performances of upstream and downstream signals under the normal and protection-mode operations. The results indicated that we could implement a scalable self-protected WDM PON by using the proposed multi-ring architecture without using either a large number of extra protection fibers or any optical amplifiers within the ring.

M. I. Anis *et al.*[43] in this paper present an investigation into the effect on the performance of an optical network based on OADM by changing different filters at the receiver side. They calculate the average BER and with the help of eye diagrams, analyze the response of the filter and compare the results with ideal filter in OADM based environment. With the help of OADM they use the network resources efficiently and provide protection to network and routing features for add and drop channel. For this they design a OADM based ring network of four nodes transmitting at 10 Gbps connected with four unidirectional non linear single mode fiber span of 10 Km.

V. Bobrovs *et al*.[44] ,this paper contains the investigation of reach improvement of dense wavelength-division-multiplexed passive optical network (DWDM-PON) using spectrum-sliced amplified spontaneous emission (ASE) source as a seed light. It is shown that flat-top AWG unit provides excellent channel separation and filtering at the same time passing sufficient high optical power from spectrally sliced ASE broadband light source. The maximum reach of the spectrum-sliced dense wavelength division-multiplexed passive optical network (SS-DWDM PON) system with data transmission speed 2.5 Gbit/s can be fairly limited by chromatic dispersion because of large optical bandwidth per channel compared to the bit rate. And therefore, dispersion degrades the performance of a SS-DWDM PON system more than it is observed in conventional laser-based system. This paper contains the investigation of improved high speed 8-channel spectrum-sliced DWDM PON system with efficient CD compensation methods like dispersion compensating fiber (DCF) and fiber Bragg grating (FBG). In this research it is shown that CD compensation has an important role for guaranteed downstream optical link performance and maximum link length of high speed SS-DWDM PON system. Results show that FBG used for CD compensation in high speed spectrum sliced dense WDM PON systems provides better accumulated CD compensation and increase link length up to 150% while DCF fiber provides up to 130% network reach improvement.

J. H. Lee *et al.*[45] they investigate the benefits of using proposed continuous-wave supercontinuum as a broadband wavelength-locking source for the implementation of extended-reach, colorless, wavelength division-multiplexed passive optical networks (WDM-PONs). More specifically, first, an extended reach WDM-PON architecture based on both the CW SC and our devised C-/L-band beam combiner is proposed, in which the optical line terminal (OLT) is based on Fabry–Pérot laser diodes (FP-LDs), whereas the optical network units (ONUs) are reflective semiconductor optical amplifiers (RSOAs). Second, a theoretical investigation on the maximum reach achievable with the proposed architecture is carried out considering Rayleigh backscattering noise and injection power limits. Only upstream signal performance is compared for the following four cases: (1) superluminescent diode (SLD) broadband source and FP-LD ONU, (2) SLD and RSOA, (3) CW SC and FP-LD, and (4) CW SC and RSOA. The combination of a CW SC injection source and RSOA-based ONUs is found to allow for the longest distance coverage. Finally, the feasibility of the proposed architecture is experimentally analyzed over a 60-km transmission fiber at 622 Mbit/s. It was found that error-free signal transmission over a 60 km fiber link could be readily achieved using the architecture at a data rate of 622 Mbit/s without using inline bidirectional optical amplifiers in the middle of a transmission fiber link. It is believed that the proposed scheme could prove to be a cost-effective, long-reach WDM PON solution for future high capacity access networks.

R. S. Kaler *et al.* [46] in this paper proposed a novel channel allocation method, based on optical Golomb ruler that allows reduction of the Four Wave Mixing (FWM) effect while maintaining bandwidth efficiency along with the algorithms has been presented. Very high-capacity, long-haul optical communication systems can be designed by wavelength division multiplexing of high-bitrate channels and by using Erbium-Doped Fiber Amplifiers (EDFAs) to periodically compensate the fiber loss. In such all-optical systems, the effects of chromatic dispersion and nonlinearities accumulate during light propagation, imposing limits on the achievable performance. Chromatic dispersion at 1.55 pm can be effectively reduced by using dispersion-shifted fiber (DSF). The use of very-low-dispersion fiber, however, enhances the efficiency of generation of FWM waves by reducing the phase mismatch naturally provided by the fiber dispersion. For this reason, crosstalk due to FWM is the dominant nonlinear effect in long-haul WDM systems using DSFs. To reduce four-wave-mixing crosstalk in high capacity long-haul repeater less WDM light wave systems, the use of the channel allocation method that involves unequal spaced channels has been proposed.

R.S. Kaler, Surinder Singh [47] in this paper, numerically simulated the ten channels at 10 Gb/s dense WDM transmission faithfully over 17,227 km using 70 km span of SMF and DCF using optimum span scheme at channel spacing 20 GHz. For this purpose, inline optimized semiconductor optical amplifiers (SOAs) and DPSK format are used. In this paper they optimized the SOA parameters for inline amplifier with minimum crosstalk and amplified spontaneous emission noise with sufficient gain at bias current 400 mA. For this bias current, constant gain 36.5 dB is obtained up to saturation power 21.35 mW. They have also optimized the optical phase modulator bandwidth for 400 mA current which is around 5.5 GHz with crosstalk-14.2 dB between two channels at spacing 20 GHz. Also, they showed the 10×10 Gb/s transmission over 70 km distance with inline amplifier has good signal power received as compared to without amplifier, even at equal quality factor. They further investigated the optimum span scheme for 5670 km transmission distance for 10×10 Gb/s with channel spacing 20 at 5.5 GHz optical phase modulator bandwidth. As we increase the transmission distance up to 17,227 km, there is increase in power penalty with reasonable quality. The impact of optical power received and Q-factor at 5670 and 17,227 km transmission distance for different span schemes for all channels has been illustrated. For launched optical power less than saturation, all channels are obtained at bit error rate floor of 10^{-10}.

R. S. Kaler *et al.*[48] in this paper simulated, for the first time, wavelength converter for future roadcast networks at 40 Gb/s using low-cost semiconductor optical amplifiers. The performance analysis is carried out for an all-optical frequency converter based on cross-phase modulation in two semiconductor optical amplifiers arranged in a MachZehnder interferometer configuration to evaluate the efficiency of conversion. The results, evaluated analytically for input, return to zero signal at a bit rate of 40 Gb/s show that conversion is possible over a wavelength separation of 1 nm between the pump and the input wavelength. Increasing the driving current can decrease the cross-phase modulation effect. The cross gain modulation scheme shows extinction ratio degradation for conversion to longer wavelengths.

R. S. Kaler, S. Singh [49] they simulated 50 nm up and down wavelength conversion for a Non-Return To Zero Differential Phase Shift Keying (NRZ-DPSK) signal using four-wave mixing in an optimized SOA at 10 Gb/s for the first time. For this they optimized the SOA parameters to achieve sufficient quality and enhancement in four wave mixing effect. This can be done in such a manner that the SOA never saturates and produces maximum four-wave mixing signals with minimum gain fluctuations. The quality of the converted signal is best before the saturation of SOA. Finally, numerically simulated cascaded wavelength converters up to 1300 km transmission distance. Ten stage cascaded wavelength conversion over 1302 km single-mode transmission is possible for 10 Gb/s NRZ-DPSK format by using FWM in SOA. Therefore, these SOA parameters can be utilized for design of optimized SOA and wide-band wavelength converter. For cascaded wavelength converter, the transmission nonlinearities in single-mode fiber can be managed by using dispersion compensating fiber with second-order dispersion management. On the whole, this wavelength converter leads to an increase in the cascadability of wavelength converters for increasing the capacity of future optical networks.

CHAPTER 3

A NOVEL RING BASED WDM-PON ARCHITECTURE FOR HIGH SPEED DATA COMMUNICATIONS

An 80 km ring architecture, based on Wavelength-Division-Multiplexed Passive Optical Network (WDM-PON), is presented and its performance is analyzed. This architecture is designed mainly for a high speed communication over a wider area. The feasibility of the architecture is analyzed using BER and Q factor analysis. At the data rate 4 Gb/s the observed values of Bit Error Rate (BER) and Q factor are 2.22×10^{-9} and 5.85 respectively. With pre and post dispersion management the data rate is further increased. BER and Q factor values after dispersion management are attained as 6.78×10^{-24} and 9.95 respectively at 4 Gb/s data rate and 2.13×10^{-9} and 6.00 respectively at 12 Gb/s data rate. The attained 12Gb/s data rate, has not been attained for WDM PON ring network yet.

3.1 INTRODUCTION

The fastest growing areas in telecom are broadband services and networks. The explosion of the Internet coupled with new video centric services has increased the demand for high bandwidth in access networks [3]. Fiber to the home, based on a PON due to its high bandwidth, cost sharing of infrastructure, and absence of active components, is considered as a good solution to this demand [4,50]. Therefore, in response to the exploding demand for high bandwidth Gigabit-PONs are being widely deployed. Services such as IP high-definition video delivery, Voice-over-IP (VoIP), social networking and cloud computing have pushed the demand for bandwidth even beyond what is achievable with today's gigabit PONs [6-9]. It is clear that wide-area broadband access networks are required to offer high speed connection services between the CO and the Remote Node (RN) . WDM-PON is a promising candidate of the low-cost subscriber networks for the fiber-to-the-home systems. Its upgradability, large capacity and flexibility are its qualities that make it such a promising candidate.

There are many possible architectures of WDM-PON. Generally, WDM-PONs are deployed as tree, bus or ring topology. In case of fiber-fault or failure, tree-based topologies cannot provide protection. Bus-based topologies are not able to balance the load among its Remote Nodes. For a remote node, the nearer to the CO, the heavier the load is; the farther from the CO, the higher is the power budget required. The ring topology can balance the load between the two branches, relax the power budget and provide protection as well [51-55]

Vjaceslavs Bobrovs *et al.* [44] demonstrated improvement in spectrum sliced DWDM PON with DCF pre-compensation. At a data rate of 2.5 Gb/s the system sustained till 23km with DCF whereas as without DCF it sustained only till 10km.

Lei Deng *et al.* [41] experimentally demonstrated propagation of data with 10.7 Gb/s DPSK downstream traffic in a WDM PON ring network over 20 km Non Zero Dispersion Shifted Fiber.

Earlier, the research has been done for communication between one CO and RN which further sends the signals to different ONUs. Many ring networks have been made till now. As the demand for broadband services is increasing day by day, new networks are required for a faster and effective communication between several stations that cover a wider area with less infrastructure cost. Dispersion is a critical effect which needs to be reduced to attain good results.

In this chapter a new WDM-PON 80km ring architecture has been proposed for communication between four stations i.e. four CO's and four RN's. The speed of data communication is severely affected by dispersion. So for a faster communication the data rate of the system has been increased by pre and post compensation of dispersion with a dispersion managed fiber.

This chapter is structured as follows: Section 2 describes the network architecture with Section 3 explaining the simulation results and at the end Section 4 summarizes the work.

3.2 NETWORK ARCHITECTURE

The network is based on a single fiber WDM ring with four nodes. This network differs from the conventional WDM PON ring networks as we have added and dropped four channels at each node i.e. a ring of four point to point WDM PONs has been made and used Optical Add Drop Multiplexers (OADM) at each node of the ring to add and drop the channels. It is demonstrated in [56] that OADM is an important network element. In ring architecture OADM can be introduced to make efficient use of network capacity, network protection, wavelength routing and many more good features. In WDM systems OADM is used for multiplexing and routing different channels or group channels carrying wavelength of light from a Single Mode Fiber. One of the main advantages of this network is that different number of channels can be installed at each node according to the requirement. Another advantage is that very high data rate can be achieved.

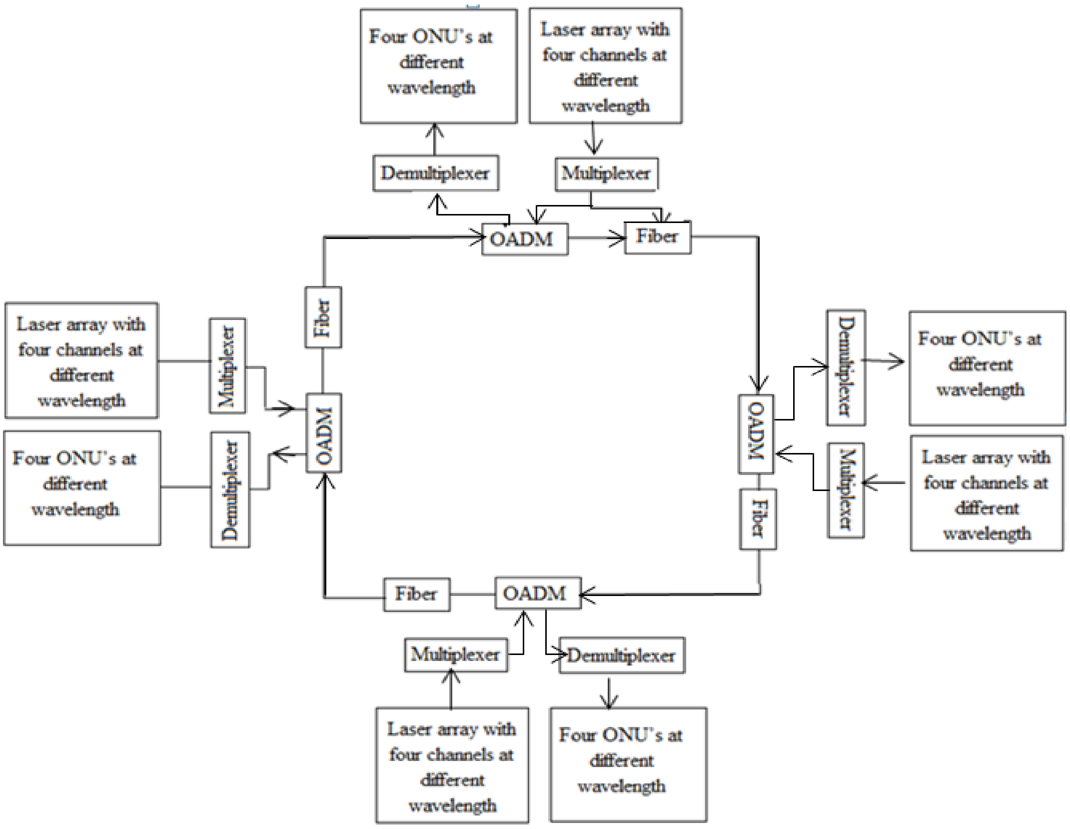


Figure 3.1: Block diagram of simulation setup

At node 1 there is a laser array which produces four beams of light at different frequencies with 100GHz channel spacing. The center frequency is taken as 193.1 THz. The produced channels are multiplexed by a WDM multiplexer and added to the ring through an OADM. It travels a distance of 20 km through the fiber and then there is another OADM through which it gets dropped out of the ring. After this it is demultiplexed again into 4 channels by a WDM demultiplexer. Then these four signals are then sent to the BER estimator and power meter for

BER and power measurements respectively. Again four channels are added in this OADM from which the earlier four channels have been dropped. These new four channels are again multiplexed and added to the ring through an OADM and dropped at the next OADM. In this way at every OADM four new channels are added and the previous four channels are dropped. OADM adds and drops a band of channels or frequencies which are further multiplexed or demultiplexed into different channels by a multiplexer or demultiplexer. This is shown in Figure 3.1.

Firstly the performance of this architecture is analyzed on basis of BER and Q factor. Then the universal fiber was replaced with a dispersion managed fiber span. Dispersion is one of the major factors which needs to be reduced in order to attain a high data rate to achieve today’s fast communication requirements. In this dispersion managed fiber span two-stage EDFA’s are used for loss compensation before and after the transmission fiber (booster/line amplifier). Dispersion compensation modules are placed at the mid-stage access points of the EDFA’s before and after the transmission fiber (pre-compensation/post-compensation). The length of pre-compensating fiber L_{Pre} as given in [57] is

$$L_{Pre} = -PreComp.\frac{D_T L_T}{D_{Pre}} \qquad (1)$$

where,

$PreComp$ =Ratio of dispersion pre-compensation with respect to accumulated dispersion in transmission fiber

D_T= dispersion coefficient of transmission fiber at reference frequency

L_T=length of transmission fiber

D_{Pre}= dispersion coefficient of pre-compensating fiber at reference frequency

Similarly the length of the post-compensating fiber L_{Post} is

$$L_{Post} = -PostComp.\frac{D_T L_T}{D_{Post}} \qquad (2)$$

where,

$PostComp$ = Ratio of dispersion post-compensation with respect to accumulated dispersion in transmission fiber

D_{Post} = dispersion coefficient of post-compensating fiber at reference frequency

3.3 RESULTS AND DISCUSSION

Firstly the the universal fiber of length 20 km was used in the ring before every node (i.e. before every OADM) and the eye diagrams and BER vs data rate plot was observed. The acceptable value of BER is less than or equal to 10^{-9}. As shown in Figure 3.2 till 4 Gb/s data rate the BER value is under acceptable range but when the data rate increases than 4 Gb/s BER becomes higher than 10^{-9}. So the system can work efficiently up to 4 Gb/s data rate.

Table 3.1: Parameters of Universal Fiber

Universal Fiber Parameter	**Value**
Length	20km
Group Refractive Index	1.47
Attenuation	0.2 dB/km
Dispersion	16×10^{-6} s/m^2
Dispersion Slope	0.08×10^{3} s/m^3
Core Area	80×10^{-12} m^3

Table 3.2: Parameters of Dispersion Managed Fiber

Dispersion Compensation Module Parameter	**Value**
Transmission Fiber Length	20km
Transmission Fiber Attenuation	200×10^{-6} dB/m
Transmission Fiber Dispersion	16×10^{-6} s/m^{2}
Transmission Fiber Dispersion Slope	80 s/m^{3}
Transmission Fiber Core Area	80×10^{-12} m^{3}
DCM Pre comp	0.5
Pre DCM loss	10dB
DCM Post comp	0.5
DCM Dispersion	-106×10^{-6} s/m^{2}
DCM Dispersion slope	-225 s/m^{3}
DCM core area	17.2×10^{-12} m^{2}

As given in [41], the WDM PON ring architecture was able to propagate data at 10.7 Gb/s data rate till 20km distance. So a dispersion managed fiber span with pre and post compensation was used in place universal fiber to further increase the data rate. The eye diagrams and BER vs. data rate plot was observed. In this plot we can see that the BER value at data rate 12 Gb/s is 2.13x 10^{-09} which is acceptable. At 13 Gb/s data rate the BER value increases from the maximum acceptable value. This is shown in Figure 3.2 and Figure 3.3. The Eye diagrams of two channels at 12 Gb/s data rate are shown in Figure 3.6 and Figure 3.7 respectively. With the dispersion compensation fiber the data rate increases from 4 Gb/s to 12 Gb/s in the same system which is more than what is achieved in conventional WDM PON rings till now.

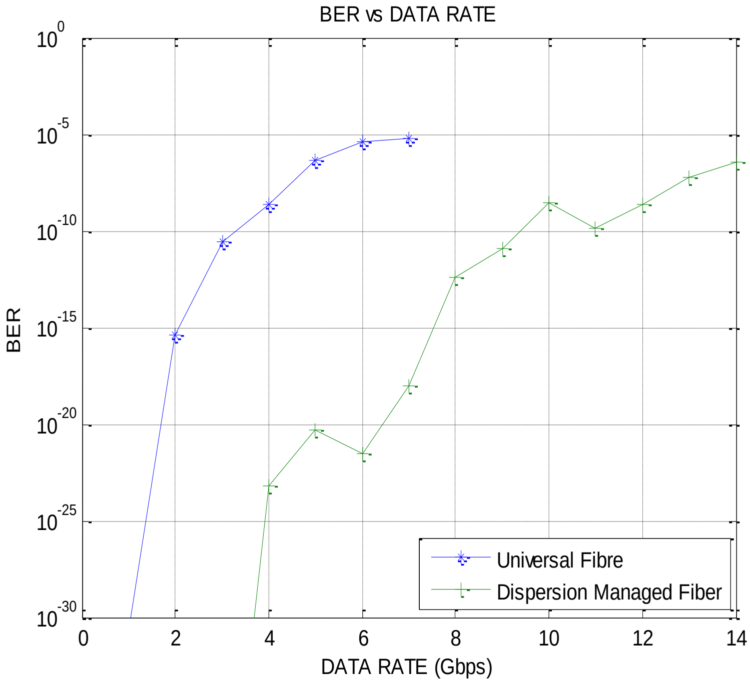


Figure 3.2: BER vs Data Rate plot at channel1

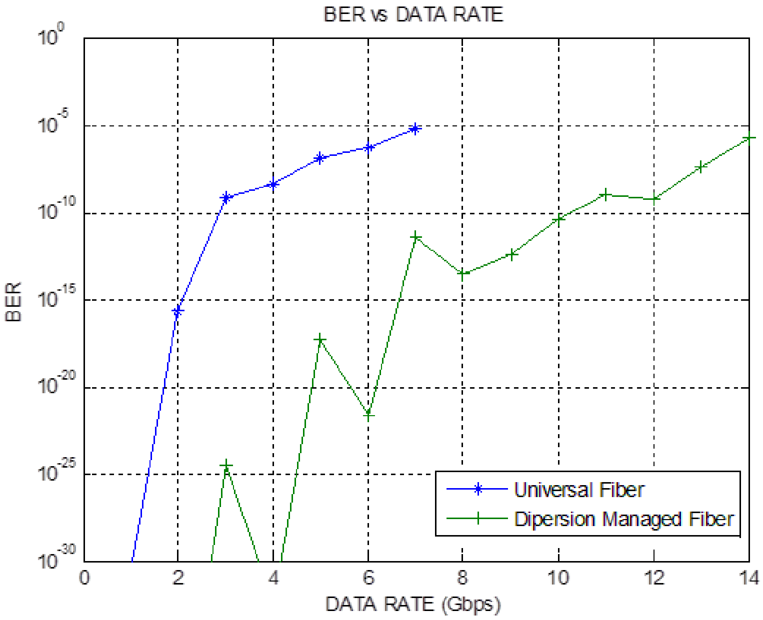


Figure 3.3: BER vs Data Rate plot at channel 16

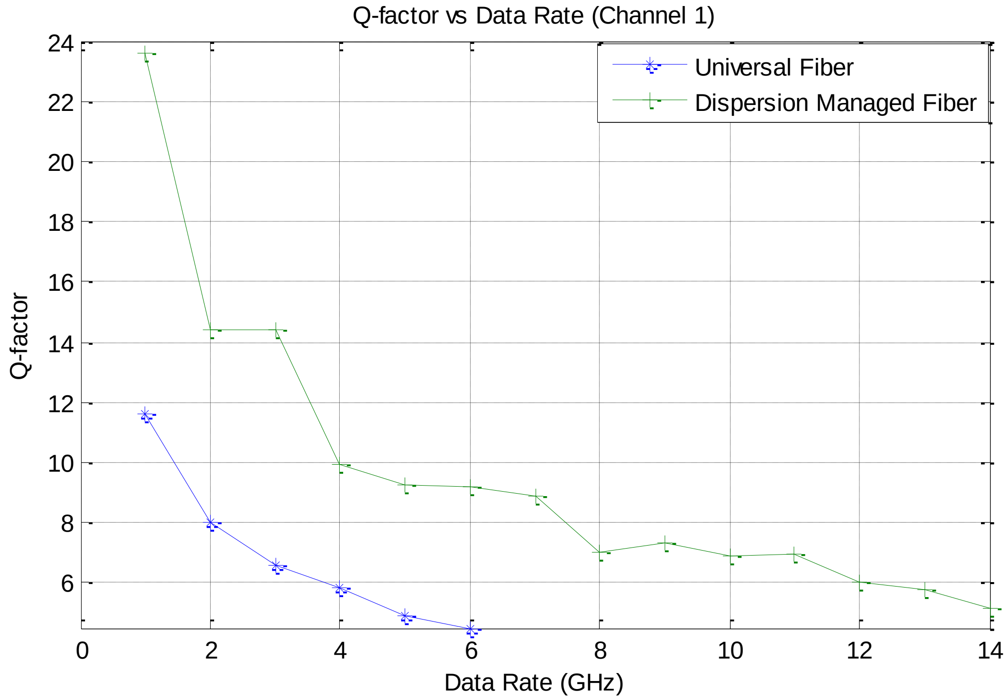


Figure 3.4: Q-factor vs Data Rate plot at channel 1

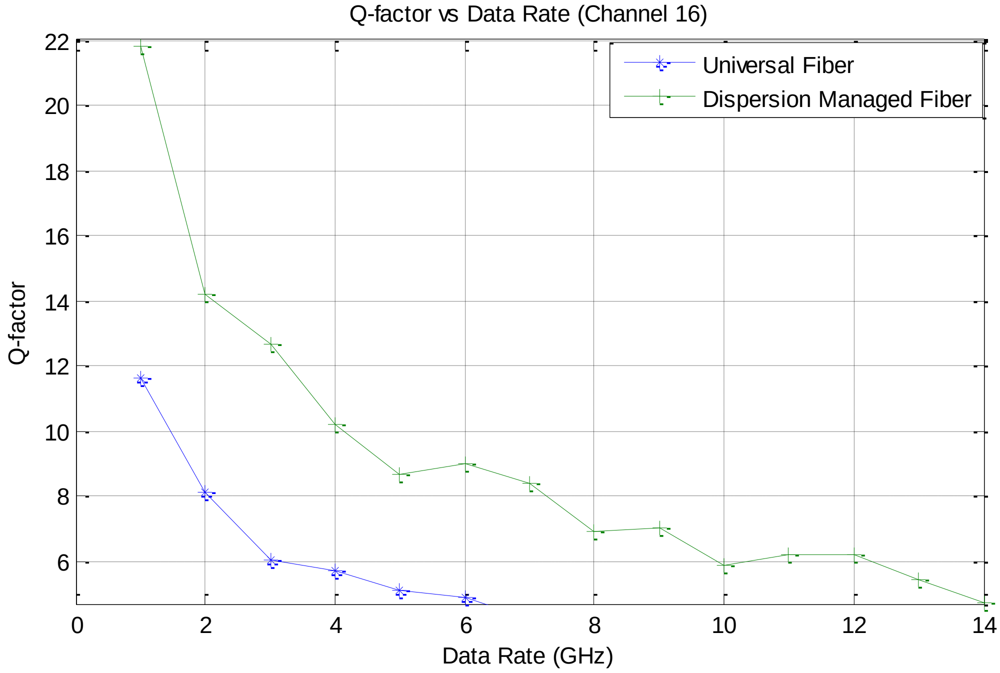


Figure3.5: Q-factor vs Data Rate plot at channel 16

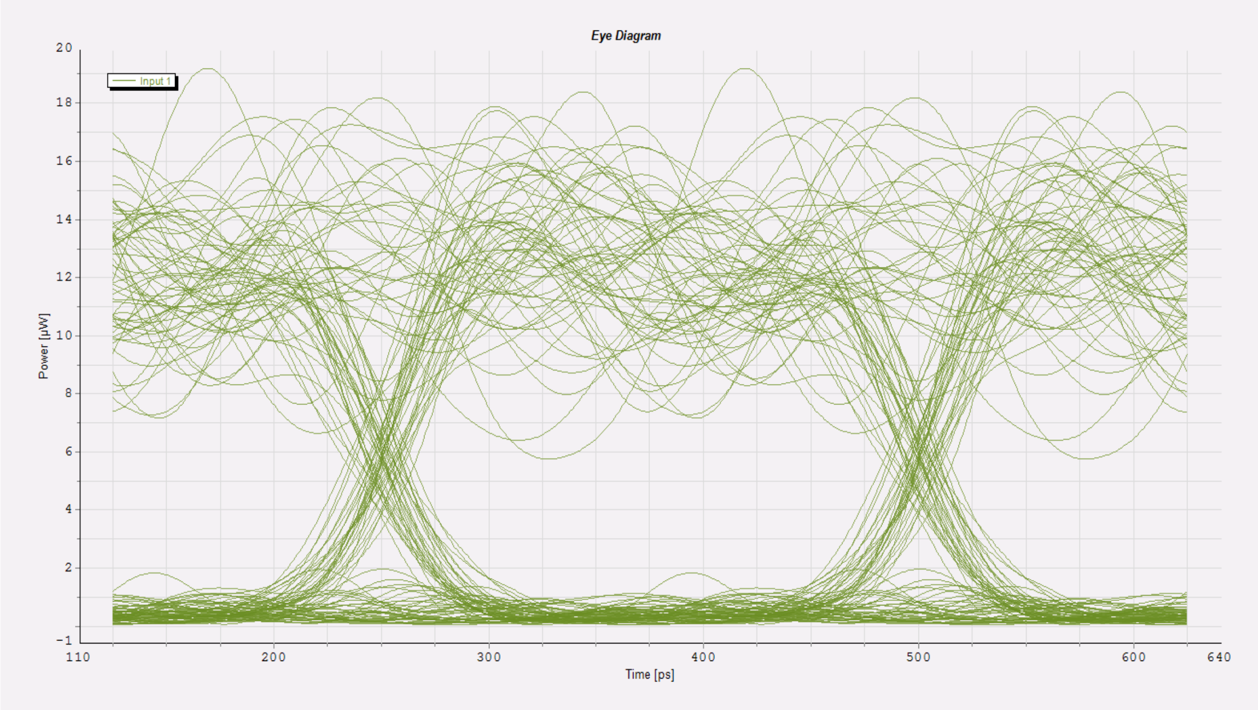


Figure 3.6: Eye Diagram of receiver channel1

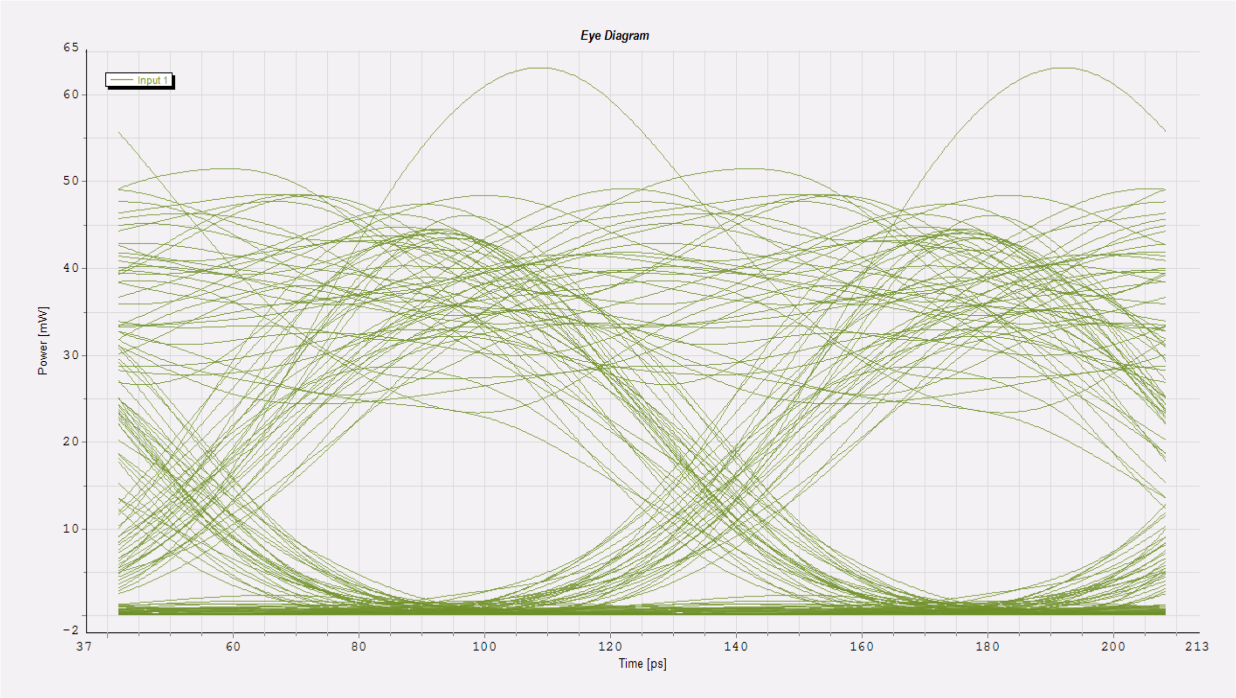


Figure 3.7: Eye Diagram of receiver channel 16

3.4 CONCLUSION

An 80km new ring architecture of WDM PON is proposed. Using VPI Transmission Maker, feasibility of the proposed architecture is evaluated by simulation results of the system performance in terms of BER and Q factor. At 4 Gb/s data rate the BER of the system is of the order of 10^{-9}. Further the data rate of the system is increased up to 12 Gb/s with the help of a pre and post dispersion compensation. As every node consists of four channels the improved data rete of each node becomes 4×12Gb/s is achieved which is more than the conventional WDM PON rings.

CHAPTER 4

PERFORMANCE ANALYSIS OF WDM-PON ARCHITECTURE USING DIFFERENT RECEIVER FILTERS

In this chapter the performance effect of a 40 Gb/s Wavelength-Division-Multiplexed Passive Optical Network (WDM-PON) is analyzed using different receiver filters namely Integrator, Bessel, Butterworth, Chebyshev, Inverse Chebyshev, Elliptic, Gaussian and Rectangular filter. The data rate and channel spacing are taken as 10Gb/s and 100GHz respectively. Among all the investigated filters, Bessel filter is considered to be the best one for this network. BER of best and worst channel for this network with Bessel filter is 2.17×10^{-13} and 6.85×10^{-9} respectively.

4.1 INTRODUCTION

The rapid expansion of high-speed internet market and data communications has accelerated the demand for broadband access. Due to this, the network costs grow quicker than revenues. In order to meet the current requirements, fiber's huge bandwidth needs to be exploited. Fiber to the home, based on a PON due to its high bandwidth, cost sharing of infrastructure, and absence of active components, is considered as a good solution to this demand [4, 50]. Therefore, Gigabit-PONs are being widely deployed these days to meet the requirement. The need of a high-speed access to transport new bandwidth-consuming services and applications such as HD TV, online gaming, VoD, video conferencing, and especially the market explosion of wireless and mobile devices that absorb a great amount of the capacity for mobile traffic backhauling [58]. These services have pushed the demand for bandwidth even beyond what is achievable with today's gigabit PONs. Wide-area broadband access networks are required to offer high speed connection services between the CO and the RN to meet this demand. WDM-PON is a promising candidate of the low-cost subscriber networks for the fiber-to-the-home systems. Its upgradability, large capacity and flexibility are its qualities that make it such a promising candidate.

M. Irfan Anis *et al*. [43] demonstrated the performance analysis of an OADM based optical network by changing the filters at receiver side. Comparison of three filters i.e. Bessel, Butterworth and Chebyshev filter was done with ideal filter for an OADM based WDM network. The results were best with Chebyshev filter.

There are many filters like Elliptic filter, Gaussian filter and rectangular filter for which the performance of WDM networks has not been analyzed yet. Moreover, to meet the current exploding demand for high bandwidth utilization WDM PON should be deployed to meet the requirements.

In this chapter effect on performance of a WDM-PON network is analyzed using different filters at receiver side. These filters are: Bessel, Butterworth, Chebyshev, Inverse Chebyshev, Elliptic, Gaussian and Rectangular filter.

This chapter is structured as follows: Section II describes the filters used with section III explaining the network architecture. Simulation results are explained in section IV and at the end Section V summarizes the work.

4.2 FILTERS

Bessel filter has excellent pulse response i.e. minimal overshoot and ringing, due to its linear phase response. It has a uniform time delay within pass band with the best step response with minimal overshoot or ringing. Along with this it has a slower initial rate of attenuation beyond the pass band compared to Butterworth and other filters. The bandwidth of Bessel filter is defined by the range of frequency where the transfer function falls below 3 dB.

The pass band magnitude response of Butterworth filter is flattest possible. At cutoff frequency the attenuation is -3dB and beyond the cutoff frequency attenuation is moderately steep. The rate of attenuation of Butterworth filter is better than Bessel filter. The pulse response of this filter is better than Chebyshev filter but has moderate overshoot and ringing.

The response of Chebyshev filter has a steeper initial rate of attenuation beyond the cutoff frequency than Butterworth. Disadvantage of this filter is amplitude variation (ripple) in pass band. Chebyshev cutoff frequency is defined the frequency at which the response falls below the ripple band. It has considerably more ringing in its pulse response than Butterworth filter.

Inverse Chebyshev filter is confined to stop band. This filter has a flat magnitude in pass band with steep rate of attenuation in transition band. It has amplitude variation (ripple) in stop band. Step response of this filter is similar to Butterworth. Inverse Chebyshev frequency is defined as the frequency where the response first enters the specified stop band.

In Elliptic filter an improved selectivity of Chebyshev filter is there by permitting ripples in both pass band and stop band. It has maximum selectivity at minimum filter order. The cutoff frequency at which the transfer function falls below the pass band ripple level, defines the bandwidth of the filter. One of the disadvantages is that it has considerably more overshoot and ringing in step response than for Butterworth and Chebyshev filters.

Gaussian filter is an ideal filter with Gaussian amplitude and zero phase of the transfer function i.e. it has a smoother transfer function without dispersion. The attenuation rate is set at transition from pass band to stop band by the filter order.

Rectangular filter is also an ideal filter but with zero attenuation within pass band and arbitrary attenuation beyond the bandwidth. It has absolutely flat magnitude and phase of frequency response. [59]

4.3 NETWORK ARCHITECTURE

A simulation scheme in VPI Transmission Maker for performance affect analysis of a WDM PON using different filters was realized. The simulation setup is shown in Figure 4.1.

As defined in ITU-T recommendation G.694.1, the frequency grid anchored 193.1 THz and channel spacing 100 GHz is used. The simulation scheme consists of four channels. The CO consists of four Optical Line Terminals (OLTs).

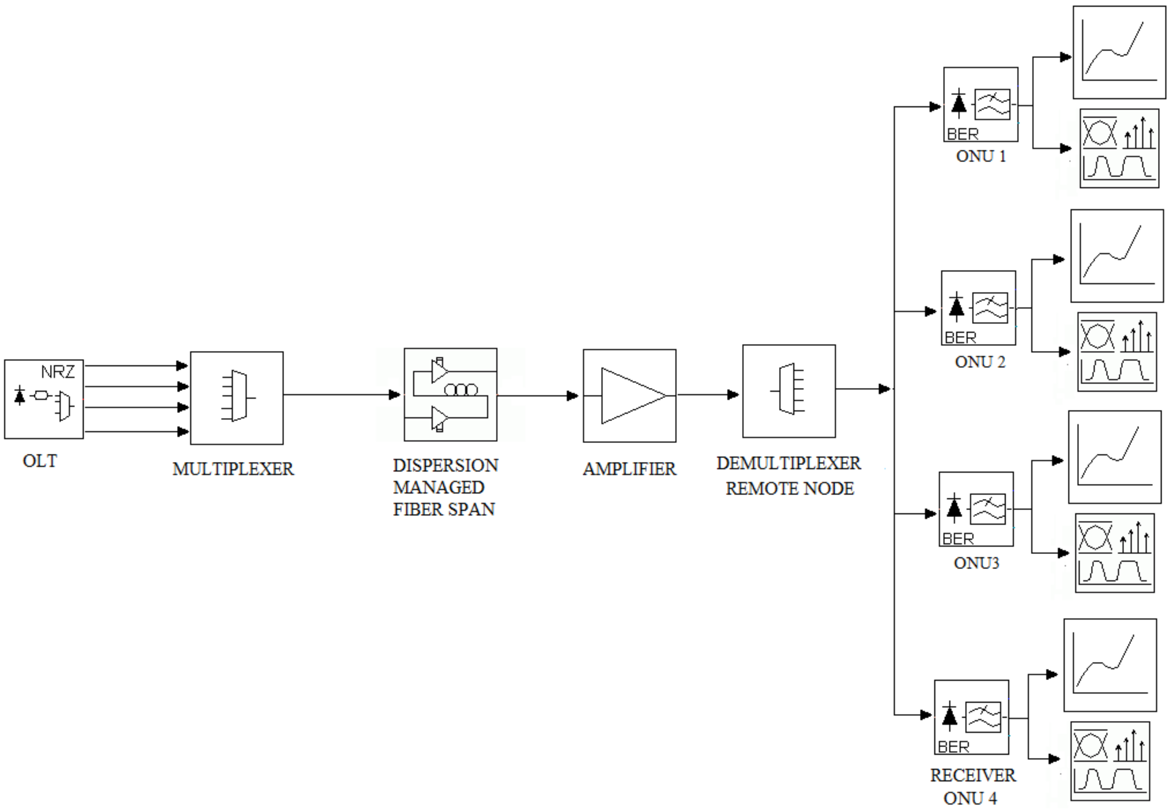


Figure 4.1: Block diagram of simulation setup

In Figure 4.1, the first component shown is a transmitter laser array which consists of four sets of: a data source, nonreturn-to-zero (NRZ) driver, continuous wave laser and external Mach-Zehnder Modulator (MZM). NRZ coding scheme is chosen, because it is one of the most easily implemented and historically dominated coding schemes in optical networks. This laser array emits 4 channels at different wavelengths at a data rate of 10 Gb/s each. These signals are multiplexed and transmitted through a dispersion managed transmission fiber 20 km in length. In this dispersion managed fiber span, two-stage EDFA's are used for loss compensation before and after the transmission fiber (booster/line amplifier). Dispersion compensation modules are placed at the mid-stage access points of the EDFA's before and after the transmission fiber (pre-compensation/post-compensation). The length of pre-compensating fiber L_{Pre} as given in [57] is

$$L_{Pre} = -PreComp.\frac{D_T L_T}{D_{Pre}} \qquad (1)$$

Where,

$PreComp$ =Ratio of dispersion pre-compensation with respect to accumulated dispersion in transmission fiber

D_T= dispersion coefficient of transmission fiber at reference frequency

L_T=length of transmission fiber

D_{Pre}= dispersion coefficient of pre-compensating fiber at reference frequency

Similarly the length of the post-compensating fiber L_{Post} is

$$L_{Post} = -PostComp.\frac{D_T L_T}{D_{Post}} \tag{2}$$

where,

$PostComp$ = Ratio of dispersion post-compensation with respect to accumulated dispersion in transmission fiber

D_{Post} = dispersion coefficient of post-compensating fiber at reference frequency

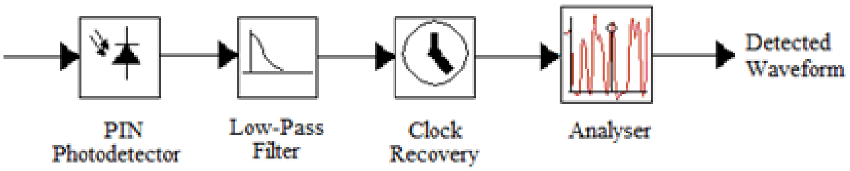


Figure 4.2: Block diagram of one ONU

Before the receiver section there is a 1×4 WDM demultiplexer which demultiplexes the signal again into 4 channels of different frequencies as in OLT. The receiver section consists of four Optical Network Units (ONUs). As shown in Figure 4.2, each ONU consists of a PIN photodiode which converts the optical signal to electrical signal, a low pass electrical filter which filters the signal to reduce its noise, a clock recovery unit and BER analyzer.

4.4 RESULTS AND DISCUSSION

In [4] the performance analysis OADM based ring network was done by changing the receiver filters namely Bessel, Butterworth and Chebyshev filter. We extend forward this work for a WDM PON network and analyze its performance for different filters namely Bessel, Butterworth, Chebyshev, Inverse Chebyshev, Elliptic, Gaussian and Rectangular filter. This analysis was done on the basis of the obtained eye diagram, Q factor and BER value for each receiver, i.e. ONU. The BER value as per ITU (International Telecommunication Union) recommendations for fiber optical transmission systems with data rate 10 Gb/s per channel should be less than or equal to10^{-9} [60]. The Q-factor values for all the filters is plotted against the fiber length and shown in Figure 4.3.

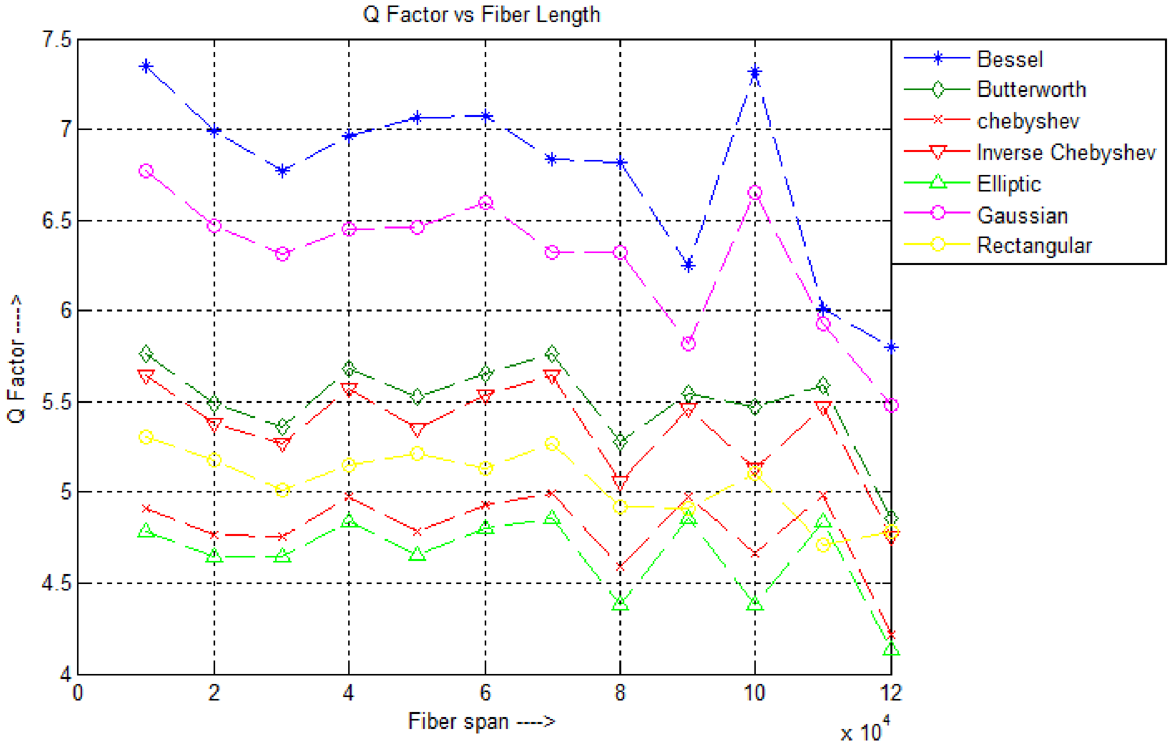


Figure 4.3 Q-Factor vs. Fiber Length

The BER values for all the filters are plotted against the fiber length and shown in Figure 4.

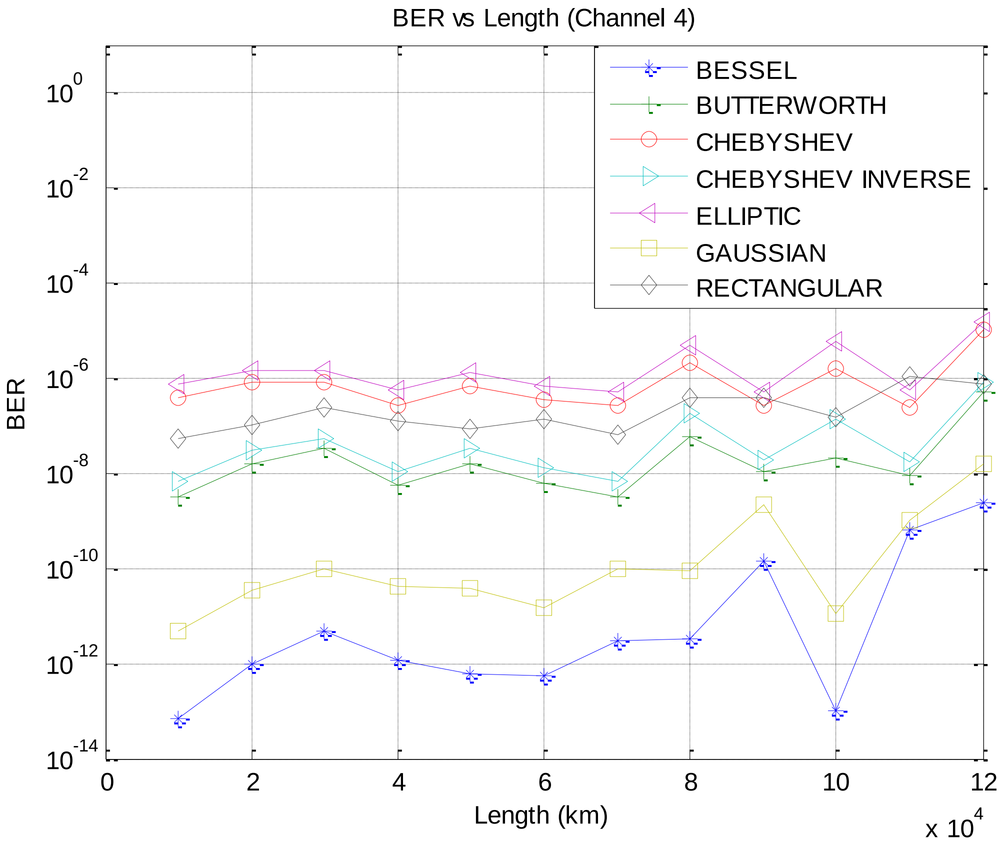


Figure 4.4 BER vs. Fiber Length

The BER values of Bessel filter with filter for four channels are 5.19×10^{-10}, 6.85×10^{-9}, 4.85×10^{-10}, 2.17×10^{-13} respectively. BER values with all other filters are more than this. So Bessel filter is considered to be the best for this network. The eye diagram of received signal at channel 1 with Bessel filter is shown in Figure 4.5. BER value remains in the range of 10^{-10}. Bessel filter is concluded to be the best filter for 40 Gb/s WDM PON network

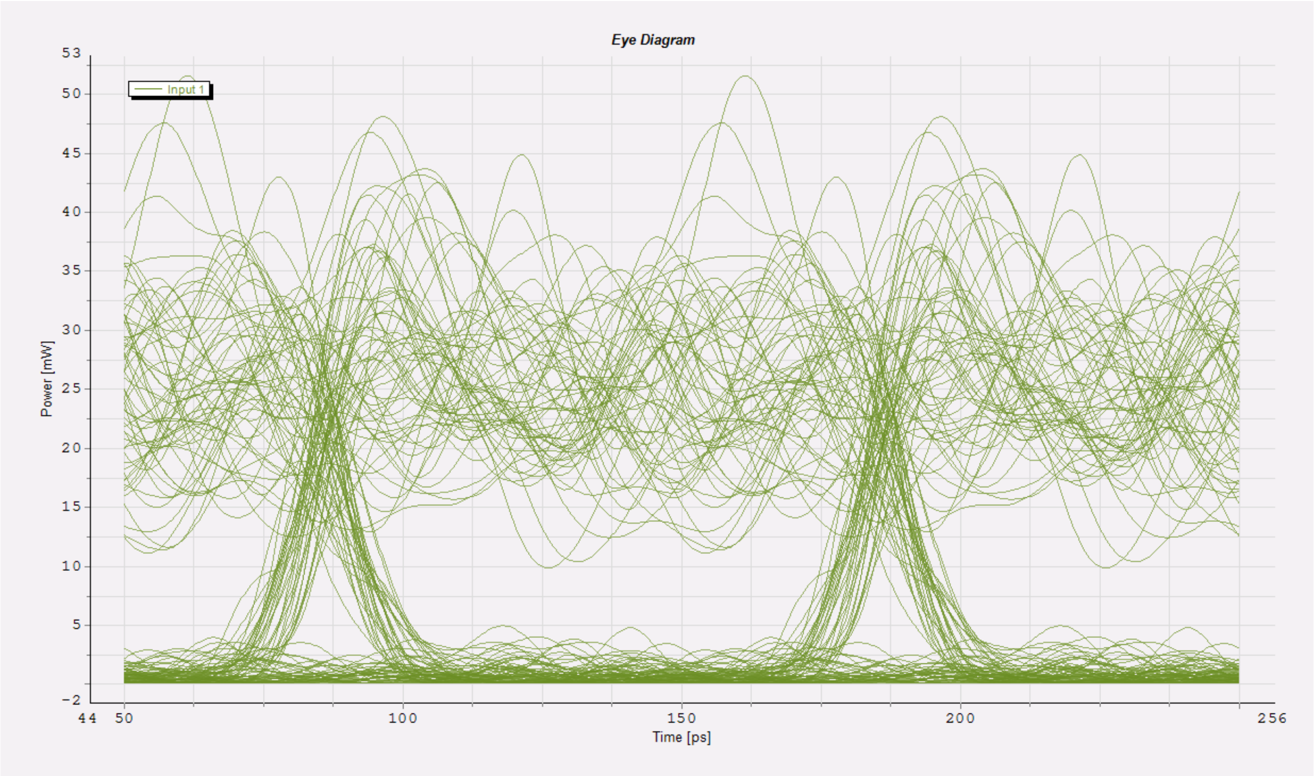


Figure 4.5: Eye Diagram of Channel 1 with Bessel Filter

4.5 CONCLUSION

Using VPI transmission maker the performance of the 40Gb/s WDM PON architecture is analyzed for different receiver filters. In [43] Chebyshev filter was found to be the best filter among Bessel, Butterworth and Chebyshev filter for an OADM based WDM ring network . In this chapter we extended the work to 40Gb/s WDM PON architecture and it is concluded that Bessel filter is the best filter among Bessel, Butterworth, Chebyshev, Inverse Chebyshev, Elliptic, Gaussian and Rectangular filter for this WDM PON network.

CHAPTER 5

LOW COST ARCHITECTURE TO INTEGRATE MULTIPLE PONS TO A LONG REACH SPECTRUM SLICED WDM NETWORK

A simple and cost effective long reach spectrum sliced WDM-PON architecture is proposed in which multiple PONs are integrated which further increase utilization of bandwidth and network sharing between the users. It is a low cost network which uses LEDs as a broadband light emitting source and further increases equipment sharing between users. The feasibility of the architecture is analyzed using BER analysis. The architecture survives up to 150+20 km fiber length where BER values of each received channel are $\leq 10^{-9}$.

5.1 INTRODUCTION

A PON connects a group of ONUs located at the subscriber premises to an OLT located at the service provider's CO. Among the various PON schemes, single channel Time-Division Multiplexed PON (TDM-PON) and multi-channel WDM-PON architectures are the two most viable candidates. TDM-PON supports a single wavelength channel in the downstream direction (OLT to ONUs) and another wavelength in the upstream direction (ONUs to OLT) [61]. WDM-PONs are emerging as the most promising future access solutions that can provide evolutionary upgrade to existing TDM-PONs. These schemes can support multiple wavelengths in either or both the upstream and downstream directions. In traditional WDM-PON, each subscriber i.e. each ONU is assigned a separate pair of dedicated upstream and downstream wavelength channels. In addition to its operational simplicity, this approach provides dedicated point-to-point optical connectivity to each subscriber with bit rate and protocol transparencies, guaranteed QoS, and increased security. TDM-PONs at present offer a satisfactory solution, they may not be able to meet future bandwidth demands. As the networks grow in terms of geographic reach, end user counts, and the scope and number of services offered, WDM-PON is clearly emerging as the most promising next-generation (NG) access solution that can deliver a symmetric 1 Gb/s or more of dedicated bandwidth per subscriber in each direction. In addition to their operational simplicity, WDM-PONs provide dedicated point-to-point optical connectivity to each subscriber with bit rate and protocol transparencies, guaranteed QoS, and increased security. [61]

Traditional WDM systems have multiple transmitter lasers operating at different wavelengths, which need to be wavelength selective for each channel and operate at a specific wavelength. It increases complexity of network architecture, cost and wavelength management. Spectrum slicing technique is one of the basic techniques available in WDM PON systems where incoherent broadband light source is used in order to reduce the cost of components and simplify the passive optical network.

J.H. Lee *et al.* [45] proposed continuous-wave supercontinuum as a broadband wavelength-locking source for the implementation of extended-reach, colorless, WDM-PONs. Error-free signal transmission over a 60 km fiber link could be readily achieved using the architecture at a data rate of 622 Mbit/s.

There is a compelling need to deliver new services to a wide number of users over a unique platform while achieving convergence (a network for all the services), flexibility (a network for every situation) and lowering overall costs (low investment and maintenance cost). The only sensible way to reduce the costs of ownership while delivering high bandwidth services is to use a very simple network, capable to fully exploit the benefit of the optical technology and fiber based networks [2].

In this chapter we propose a simple and cost effective long reach Spectrum Sliced WDM-PON (SS WDM-PON) architecture in which multiple PONs are deployed which further increase utilization of bandwidth and network sharing between the users.

5.2 NETWORK ARCHITECTURE

Spectrum slicing technique is one of the basic techniques available in WDM PON systems where incoherent broadband light source is used in order to reduce the cost of components and simplify the passive optical network. LED is a good light source for generating equally spaced multi-wavelength channels. One of the advantages of using LED over laser is its lower cost. Another advantage is lesser complexity of network, as there is no need to set the center frequency of each laser. This is done by a wavelength multiplexer on its own.

A simulation scheme for performance analysis of the proposed spectrum sliced WDM PON architecture was realized in VPI Transmission Maker. The simulation setup is shown in Figure 5.1.

The frequency grid anchored 193.1 THz and channel spacing 250 GHz is used. Four wavelength channels are considered in the simulation network. The CO consists of four OLTs which means four LEDs are used.

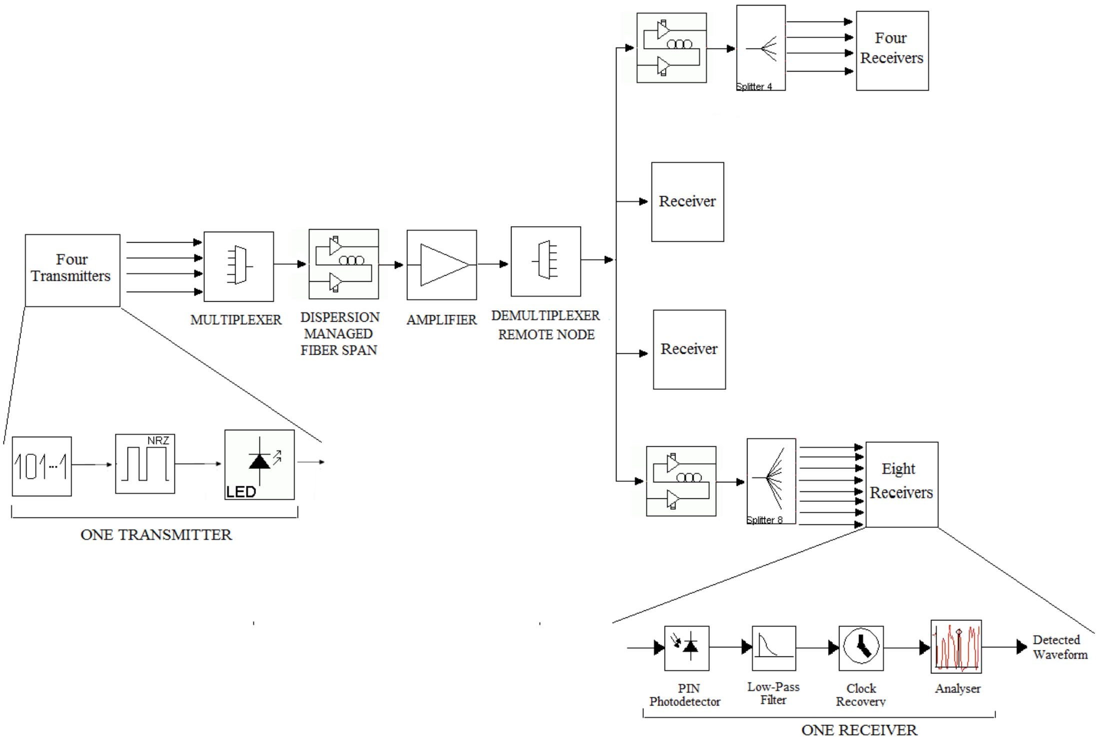


Figure 5.1: Simulation Setup

In Figure 5.1, the OLT consists of four sets of: a data source, NRZ driver and LED. The reason of choosing NRZ coding scheme is that it is one of the most easily implemented and historically dominated coding schemes in optical networks. These emit light which is sent to a wavelength multiplexer where it is divided into four channels at different wavelengths at a data rate of 1 Gb/s each. These signals transmitted through a dispersion managed transmission fiber. In this dispersion managed fiber span, two-stage EDFA's are used for loss compensation before and after the transmission fiber (booster/line amplifier). Dispersion compensation modules are placed at the mid-stage access points of the EDFA's before and after the transmission fiber (pre-compensation/post-compensation). The length of pre-compensating fiber L_{Pre} as given in [57] is

$$L_{Pre} = -PreComp.\frac{D_T L_T}{D_{Pre}} \tag{1}$$

Where,

$PreComp$ =Ratio of dispersion pre-compensation with respect to accumulated dispersion in transmission fiber

D_T= dispersion coefficient of transmission fiber at reference frequency

L_T=length of transmission fiber

D_{Pre}= dispersion coefficient of pre-compensating fiber at reference frequency

Similarly the length of the post-compensating fiber L_{Post} is

$$L_{Post} = -PostComp.\frac{D_T L_T}{D_{Post}} \tag{2}$$

where,

$PostComp$ = Ratio of dispersion post-compensation with respect to accumulated dispersion in transmission fiber

D_{Post} = dispersion coefficient of post-compensating fiber at reference frequency

The use of optimize semiconductor amplifier can also be used to achieve larger optical link length [62]. Therefore, an amplifier is used after the fibel length. Before the receiver section there is a wavelength demultiplexer which demultiplexes the signal again into 4 channels of different frequencies as in OLT. When the signal is demultiplexed, at channel 1 and channel 4 the data transmits up to 20km length again and channel 2 and channel 3 are received by their respective receivers. The receiver section consists of a PIN photodiode which converts the optical signal to electrical signal, a low pass electrical filter which filters the signal to reduce its noise, a clock recovery unit and BER analyzer. At channel1 and channel 2 after traversing the length of 20 km there is a passive splitter which splits the signal into four parts at channel 1 and eight parts at channel 2. These split signals further increase the network sharing. Finally these split signals are received by their respective receivers.

5.3 RESULTS AND DISCUSSION

In order to demonstrate the feasibility of proposed architecture, the simulation of proposed architecture was performed using VPI Transmission Maker. The power spectrum of the signal from LEDs after wavelength multiplexing is shown in Figure 5.2

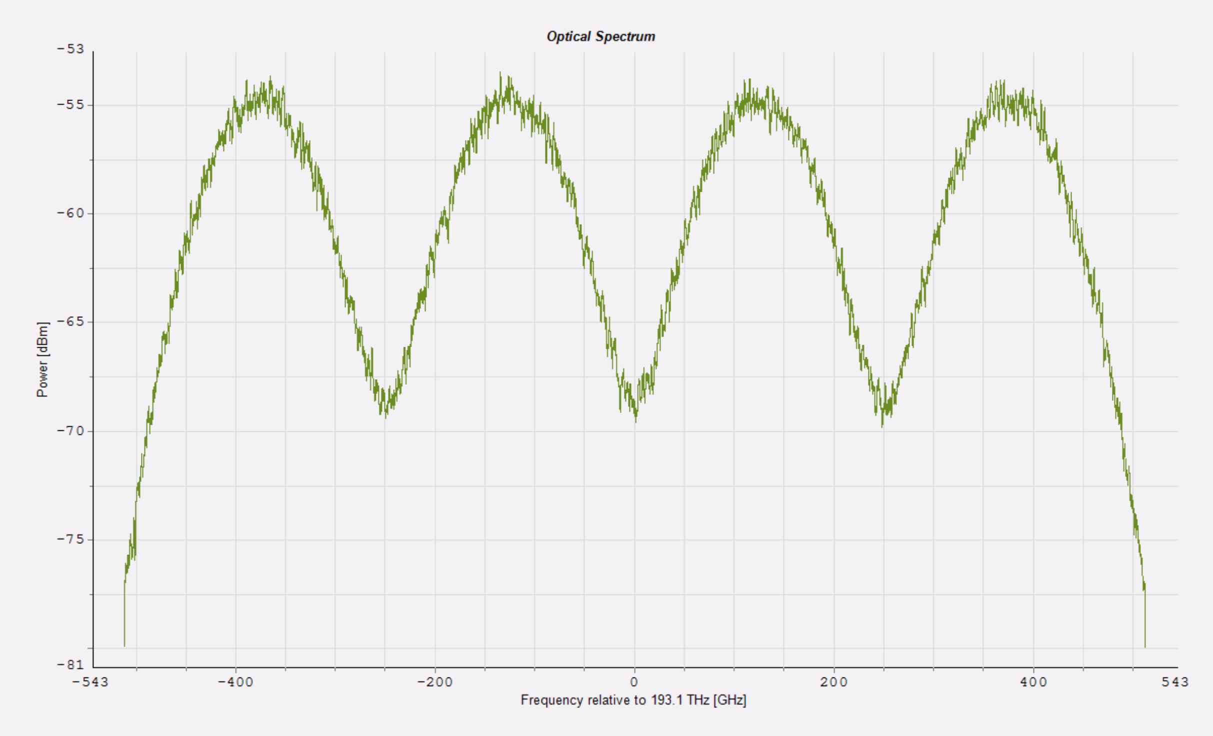


Figure 5.2: Power Spectrum Of The Signal From LEDs After Wavelength Multiplexing

Four peaks of four transmitted channels are seen in Figure 5.2. This signal passes through fiber to wavelength demultiplexer. The fiber parameters are shown in Table 5.1

Table 5.1: Transmission Fiber Parameters

Dispersion Compensation Module Parameter	**Value**
Transmission Fiber Length	20km
Transmission Fiber Attenuation	200×10^{-6} dB/m
Transmission Fiber Dispersion	16×10^{-6} s/m^2
Transmission Fiber Dispersion Slope	80 s/m^3
Transmission Fiber Core Area	80×10^{-12} m^3
DCM Pre comp	0.5
Pre DCM loss	10dB
DCM Post comp	0.5
DCM Dispersion	-106×10^{-6} s/m^2
DCM Dispersion slope	-225 s/m^3
DCM core area	17.2×10^{-12} m^2

The received signal is analyzed on the basis of BER values and eye diagrams. The BER values of each channel are plotted against the fiber length. These values are plotted in Figure 5.3 and Figure 5.4.

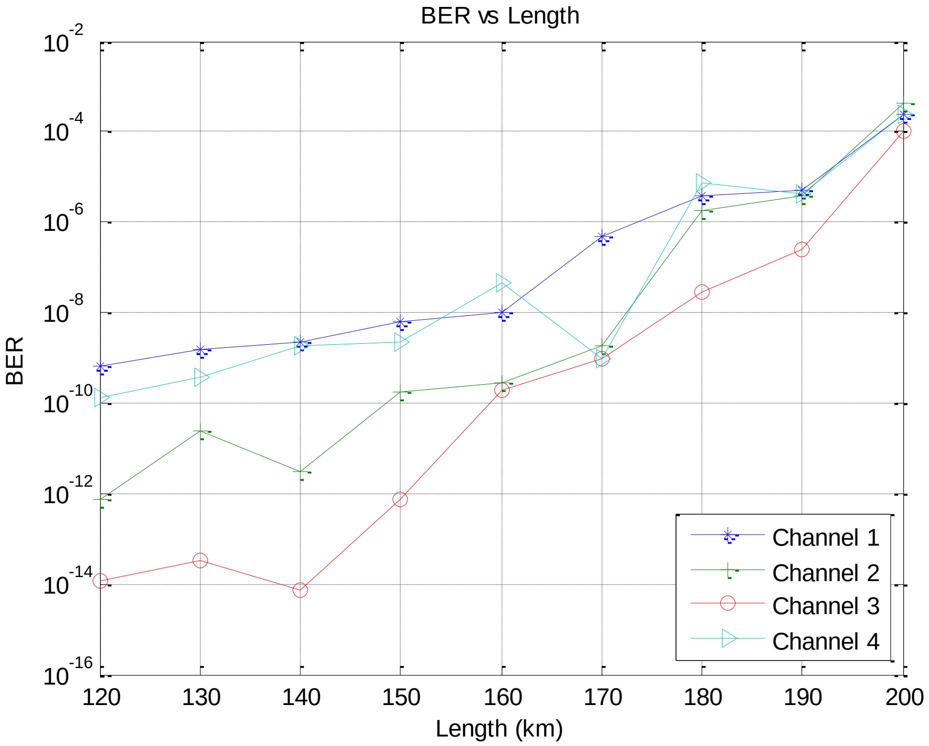


Figure 5.3 BER vs Length of the fiber

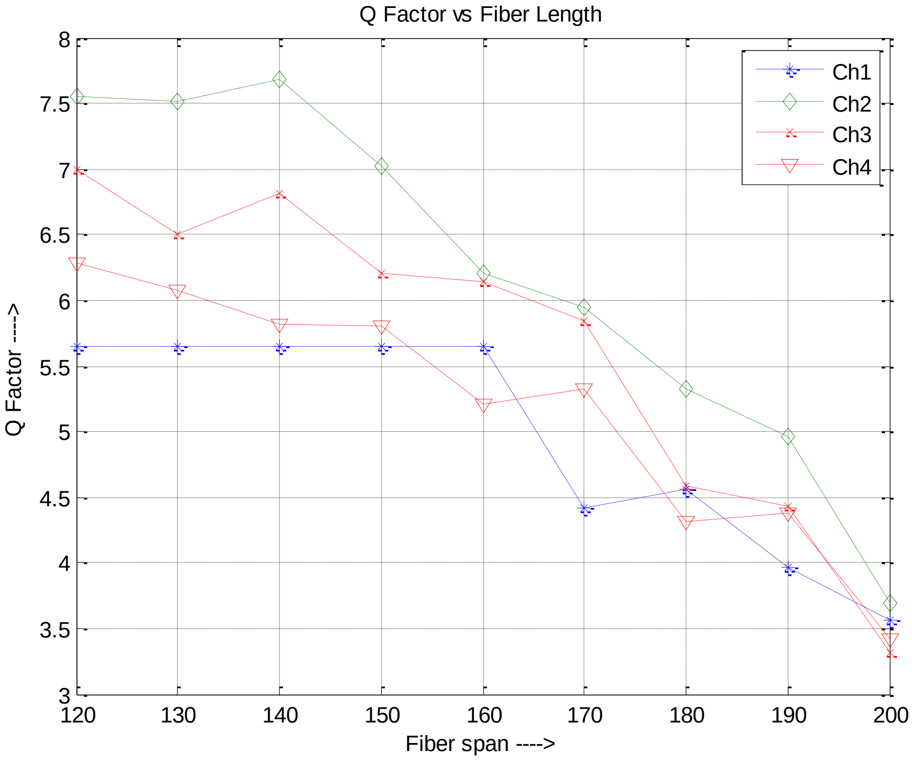


Figure 5.4 Q-factor vs. length of fiber

The Eye Diagram of one receiver, out of four receivers of channel 1, is shown in Figure 5.5. The Eye Diagrams channel 2 and channel3 are shown in Figure 5.6 and Figure 5.7 respectively. Figure 5.8 shows the Eye Diagram of one receiver, out of eight receivers of channel 4

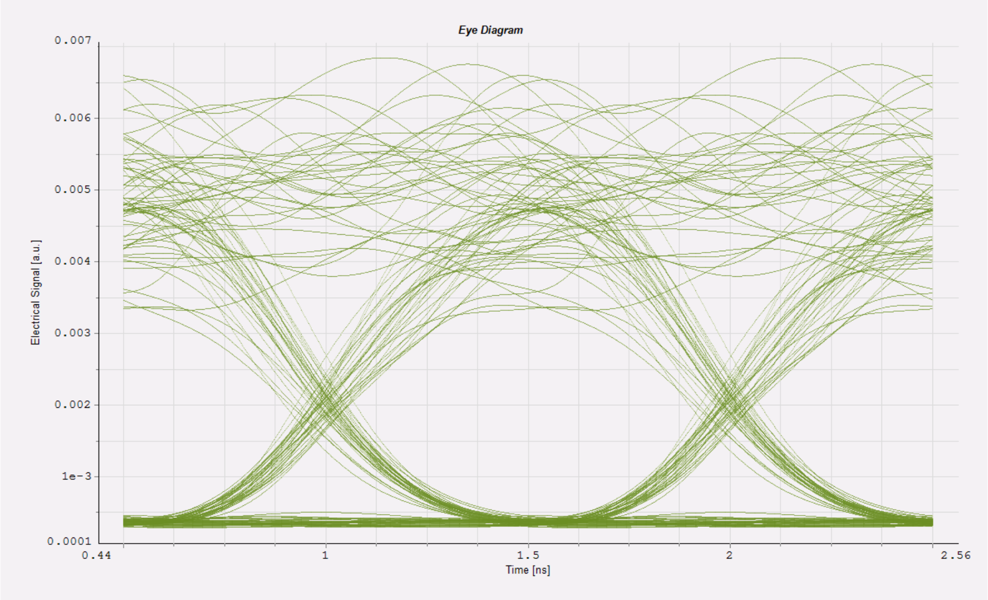


Figure 5.5: Eye Diagram of one receiver of channel 1

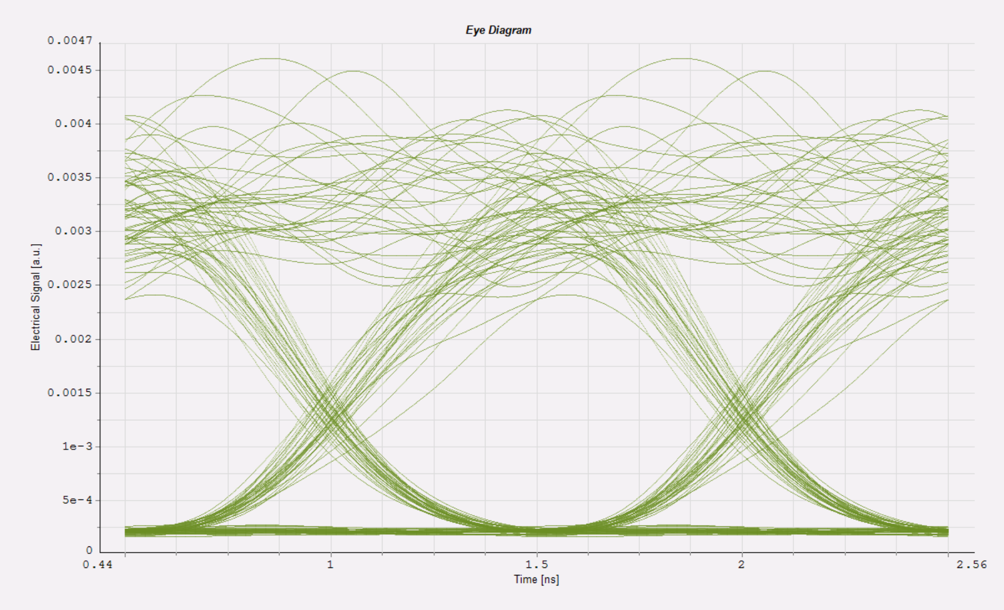


Figure 5.6: Eye Diagrams channel 2

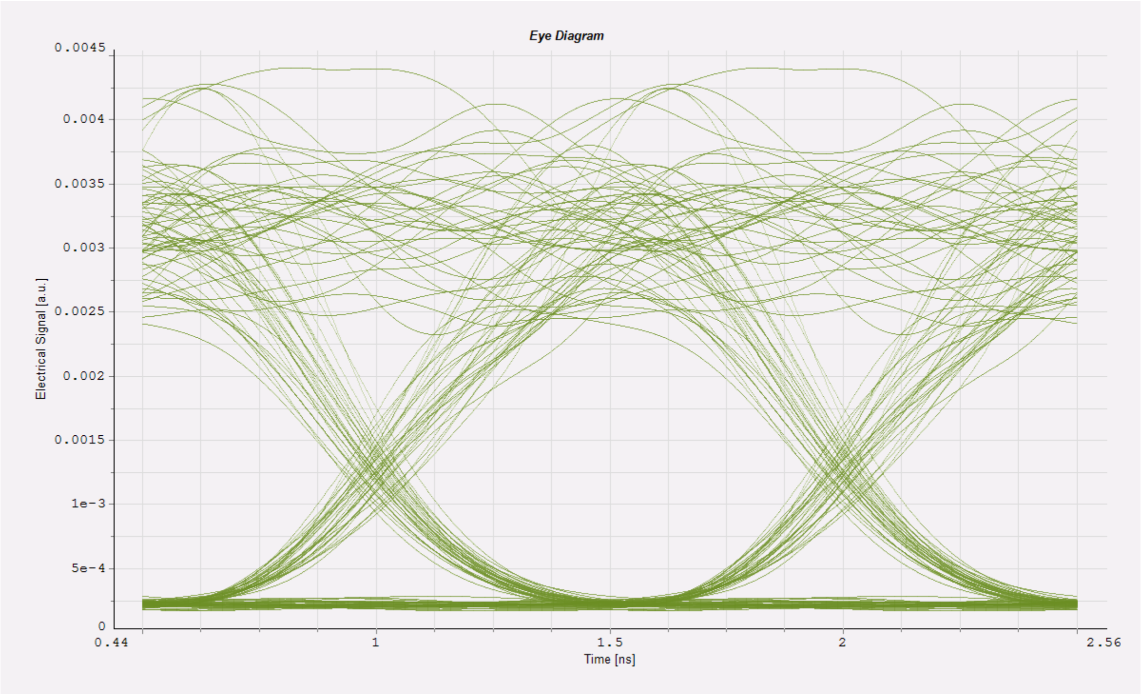


Figure 5.7: Eye Diagram of channel 3

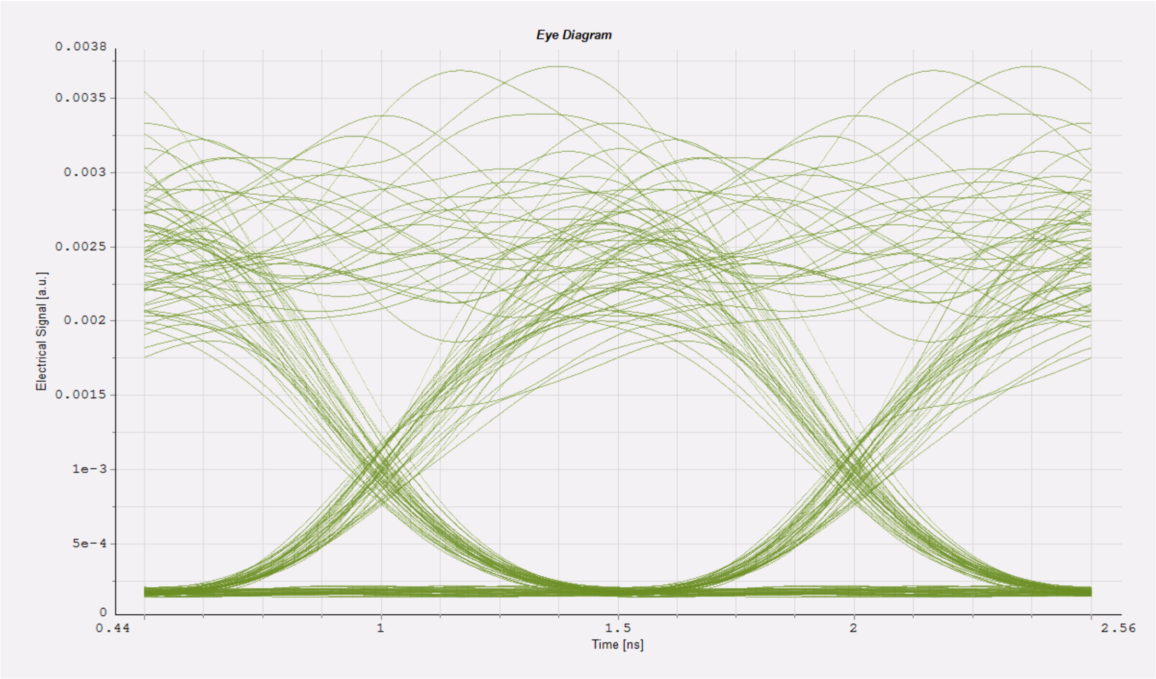


Figure 5.8: Eye Diagram of one receiver of channel 4

In [45] proposed scheme transmitted the data over a 60 km fiber link using the architecture at a data rate of 622 Mbit/s. in this chapter it is seen from the above results that architecture is feasible till 150 km fiber length. The BER values of each channel at 150 km are 6.51×10^{-09}, 1.83×10^{-10}, 7.26×10^{-13} and 2.13×10^{-09} respectively. For a fiber length more than 150km the BER value is obtained in the range of 10^{-08} which is higher than the acceptable value 10^{-09}. Therefore, it is concluded the data can be transmitted up to 150 km at a data rate of 1 Gb/s.

5.4 CONCLUSION

A low cost spectrum sliced WDM network with multiple PONs is proposed. LEDs are used as a low cost broadband light source in this network. The feasibility of the architecture is analyzed on the basis of BER values and eye diagrams using VPI Transmission Maker. The BER values of all the four channels at 150km fiber length are 6.51×10^{-09}, 1.83×10^{-10}, 7.26×10^{-13} and 2.13×10^{-09} respectively. It is concluded that error-free signal transmission over a 150 km fiber link could be readily achieved using the architecture at a data rate of 1 Gb/s. It is believed that the proposed scheme could prove to be a cost-effective, long-reach WDM PON solution for high capacity access networks.

CHAPTER 6

CONCLUSIONS, RECOMMENDATIONS AND FUTURE PROSPECT

6.1 CONCLUSIONS AND RECOMMENDATIONS

This chapter provides the summary of research work done in this dissertation. First the conclusions have been made from this study, then the recommendations have been given on the basis of the conclusions and then suggestions for future research are discussed. The major results obtained in this thesis are summarized below

1. An 80 km new ring architecture of WDM PON is proposed. The feasibility of the proposed architecture is evaluated by simulation results of the system performance in terms of BER, Q factor and eye diagrams. At 4 Gb/s data rate the BER of the system is of the order of 10^{-9}. Till 4 Gb/s data rate the BER value is under acceptable range but when the data rate increases than 4 Gb/s BER becomes higher than $10^{-}9$. Further a dispersion managed fiber span with pre and post compensation was used in place universal fiber to further increase the data rate. The eye diagrams and BER vs. data rate plot was observed. In this plot we can see that the BER value at data rate 12 Gb/s is 2.13x 10^{-09} which is acceptable. At 13 Gb/s data rate the BER value increases from the maximum acceptable value. The data rate of the system is increased up to 12 Gb/s with the help of a pre and post dispersion compensation. As every node consists of four channels the improved data rete of each node becomes 4×12Gb/s is achieved which is more than the conventional WDM PON With the dispersion compensation fiber the data rate increases from 4 Gb/s to 12 Gb/s in the same system which is more than what is achieved in conventional WDM PON rings till now.

   The proposed ring architecture is recommended for high speed communication. Dispersion management is recommended wherever the speed of data communication needs to be increased.
2. The performance effect analysis of a 40 Gb/s WDM PON network and analyze its performance for different filters namely Bessel, Butterworth, Chebyshev, Inverse Chebyshev, Elliptic, Gaussian and Rectangular filter. This analysis was done on the basis

of the obtained BER value for each receiver, i.e. ONU. The BER value as per ITU recommendations for fiber optical transmission systems with data rate 10 Gb/s per channel should be less than or equal to10^{-9}. The BER values of Bessel filter for four channels are 5.19×10^{-10}, 6.85×10^{-9}, 4.85×10^{-10}, 2.17×10^{-13} respectively. BER values with all other filters are more than this. So Bessel filter is considered to be the best for WDM PON network**.** It is recommended to use Bessel filter, amongst other electrical filters in WDM PON networks.

3. A simple and cost effective long reach spectrum sliced WDM-PON architecture is proposed in which multiple PONs are integrated which further increase utilization of bandwidth and network sharing between the users. It is a low cost network which uses LEDs as a broadband light emitting source and further increases equipment sharing between users. In order to demonstrate the feasibility of proposed architecture, the simulation of proposed architecture was performed using VPI Transmission Maker. The feasibility is analyzed using BER analysis. The architecture survives up to 150km fiber length and 20 km after wavelength demultiplexing where BER values of each received channel are $\leq10^{-9}$. For a fiber length more than 150km the BER value is obtained in the range of 10^{-08} which is higher than the acceptable value 10^{-09}. Therefore, it is concluded the data can be transmitted up to 150+20 km at a data rate of 1 Gb/s. It is believed that the proposed scheme could prove to be a cost-effective, long-reach WDM PON solution for high capacity access networks.

6.2 FUTURE PROSPECT

During the course of this dissertation, several avenues for continuation of this study became evident. The topics which were considered worthwhile are summarized below

We have neglected all other fiber nonlinearities Cross phase modulation, Four Wave Mixing, Simulated Raman Scattering and Simulated Brillouin scattering. Considering all these nonlinearities, it is of interest to see how these results change.

In this dissertation the polarization effects have not been taken into account. Simulation studies can be done for same architectures while taking into account the polarization effects.

The comparison of different receiver filters can be done on the basis of simulation results. It will be interesting to prove these results mathematically.

We have used channel spacing of 100 GHz and 250 GHz. This can be further reduced for more bandwidth utilization and some other techniques can be introduced for further network sharing.

In this dissertation our focus is optical access networks but the real world implementation of access networks will be a combination of optical fiber links, existing twisted pair copper lines, wireless LAN and free space optics. The interfaces between different technologies and media in hybrid access create interesting research.

REFERENCES:

[1] H. Shinohara, “Broadband access in Japan: Rapidly growing FTTH market,” *IEEE Commun. Mag.*, vol. 43, no. 9, pp. 72–78, 2005.

[2] Luca Giorgi, Fabio Cavaliere, Pierpaolo Ghiggino, Filippo Ponzini, Alberto Bianchi, and Antonio D’Errico, “Characterization of a High Capacity Multi-User Optical Access Network Using 1 Gb/s 16 QAM Subcarrier Multiplexing”, *J. of Lightwave Tech,* vol. 27, no. 9, 2009

[3] Sang-Mook Lee, Sil-Gu Mun, Min-Hwan Kim and Chang-Hee Lee, “Demonstration of a Long-Reach DWDM PON for Consolidation of Metro and Access Networks”, *J. of Lightwave Tech*, vol. 25, no. 1, 2007

[4] S.-J. Park, C.-H. Lee, K.-T. Jeong, H.-J. Park, J.-G. Ahn, and K.-H. Song, “Fiber-to-the-home services based on wavelength-division-multiplexing passive optical network,” *J. of Lightwave Tech*., vol. 22, no. 11, pp. 2582– 2591, Nov. 2004.

[5] H. Shinohara, “Broadband access in Japan: Rapidly growing FTTH market,” IEEE Commun. Mag., vol. 43, no. 9, pp. 72–78, 2005.

[6] J. Kani and N. Yoshimoto, “Next generation PONs: An operator’s view,” presented at the *Eur. Conf. Optical Communication (ECOC),* Vienna, Austria, 2009, Paper 5.7.4.

[7] J. Kani, *et al*., “Next-generation PON—Part I: Technology roadmap and general requirements,” *IEEE Comm. Mag.*, vol. 47, pp. 50–57, 2009.

[8] *10-Gigabit-Capable Passive Optical Network (XGPON)*: Physical Media Dependent (PMD) Layer Specification Jan. 2010, ITU-T G.987.2.

[9] *10-Gigabit-Capable Passive Optical Network (XGPON) Systems*: Transmission Convergence Layer Specification, 2010, ITU-T G.987.3.

[10] R. P. Davey *et al*., “Long-reach passive optical networks,” *J. of Lightwave Tech*, vol. 27, pp. 273–291, 2009.

[11] Gong-Ru Lin, *et al.*, “Long-Cavity Fabry–Perot Laser Amplifier Transmitter With Enhanced Injection-Locking Bandwidth for WDM-PON Application”, *J. of Lightwave Tech*, Vol. 28, No. 20, 2010

[12] R. Davey *et al*., “Options for future optical access networks,” *IEEE Commun. Mag.*, vol. 44, no. 10, pp. 50–56, 2006.

[13] Masamichi Fujiwara, *et al.*, "Centralized Frequency Stabilization With Wide Capture Range Using MZI-AWG in DWDM-PON", *IEEE Photonics Tech. Letts*, vol. 20, no. 19, 2008.

[14] G. Talli, *et al.* "Long reach hybrid DWDM-TDM PON with high split ratio employing centralized light source," *J. of Optical Networking*, vol. 6, pp. 765–776, 2007.

[15] H. Suzuki *et al.* "Application of super-DWDM technologies to terrestrial terabit transmission systems" *J. of Lightwave Tech*, vol 24, Issue: 5, pp 1998 - 2005, 2006.

[16] K. Grobe, J.-P Elbers, "PON in adolescence: from TDMA to WDMPON" *IEEE Commun. Mag.*, vol. 46 (1), pp. 26-34, 2008.

[17] Darren P Shea and John E Mitchell, "Architecture to Integrate Multiple PONs with Long Reach DWDM Backhaul", *IEEE Journal On Selected Areas In Communications*, vol. 27, no. 2, 2009

[18] Biswanth Mukherjee, "Enabling Technologies: Building Blocks", *Optical WDM networks*, Springer, 2006.

[19] F. B. Shepherd and A. Vetta, "Lighting Fibers in a Dark Network", *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 9, pp. 1583-1588, 2004.

[20] C. H. Lee, *et al.*, "Fiber To The Home Using A PON Infrastructure," *Journal Lightwave Technology*, Vol. 24, pp. 4568–4583, 2006.

[21] L. Kazovsky, *et at.*, "Next-Generation Optical Access Networks," *J. of Lightwave Tech*, vol. 25, no. 11, pp. 3428-3442, 2007.

[22] Jong-Won Kim, "An Optimized ATM-PON Based FTTH Access Network," *International Conference on Information, Communications and Signal Processing ICICS*, 1997.

[23] A Banerjee, *et al.*, "A review of wavelength-division multiplexed passive optical network (WDM-PON) technologies for broadband acces", *Optical Society Of America*, 2005.

[24] F. J. Effenberger, *et at.*, "Advances in broadband passive optical networking technologies," *IEEE Communications Magazine*, vol. 39, no. 12, pp. 118-122, 2001.

[25] H.H. Lu, W.J. Wang, P.C. Lai, "A hybrid CATV/256-QAM/OC-192 WDM transport system using SMF and RDF combination", *Optics Communication*, vol. 223, pp. 315, 2003.

[26] C.C. Lee, *et al*., “Hybrid 10-Gb/s, 2.5-Gb/s, 64-QAM, and AM-VSB high-capacity wavelength-division-multiplexing transport systems using SMF and LEAF fibers”, *IEEE Photonics Tech. Lett*, vol. 14 , pp. 230, 2002

[27] M. Khanal, *et al*., “Selective broadcasting of digital video signals over a WDM passive optical network”, *IEEE Photonics Tech. Lett*, vol. 17 , pp. 1992, 2005.

[28] S.J. Park, *et al*., “Fiber-to-the home services based on wavelength division-multiplexing passive optical network*”, J. of Lightwave Tech*, vol. 22 , pp. 2582, 2004.

[29] E.S. Son, *et al*., “Bidirectional WDM passive optical network for simultaneous transmission of data and digital broadcast video service”, *Journal Lightwave Technology*, vol.21, pp. 1723, 2003.

[30] R.S. Kaler *et al*., “Approximate and Exact Small Signal Analysis for Single-Mode Fiber Near Zero Dispersion Wavelength with Higher Order Dispersion”, *Fiber and Integrated Optics*, vol.21 no. 5,pp. 391-415, 2002.

[31] K.S. Kim,"On the evolution of PON based FTTH solutions", *Information Sciences*, vol 149, pp 21-30, 2002.

[32] Fu-Tai An *et al*., “Evolution, Challenges and Enabling Technologies for Future DWM based Optical Access Networks”, *Photonics and Networking research Laboratory*, Stanford Unversity,

[33] Samir Chatterjee, Suzanne Pawlowski, “Enlightening the effects and implications of nearly infinite bandwidth”, communications of the ACM, Vol. 42, No.6, pp 74-83, 1999

[34] B. Chen, C. Gan, “Novel architecture of WDM-PON based on single-fiber ring topology featuring protection and dynamic wavelength assignment,” *International Journal for Light and Electron Optics*, vol. 124, no. 3, pp. 234-237, 2013

[35] H. Suzuki *et al.*, “Demonstration and Performance of Colorless ONU for Coexistence-Type WDM-PON Using a Wavelength-TunableL-Band DWDM-SFP Transceiver,” *IEEE Photonics Tech. Lett.*, vol. 20, no. 19, 2008.

[36] S. M. Lee *et al.*, “Demonstration of a Long-Reach DWDM-PON for Consolidation of Metro and Access Networks,” *J. of Lightwave Tech.*, vol. 25, no. 1, 2007

[37] C. W. Chow *et al.*’ “Rayleigh Noise Reduction in 10-Gb/s DWDM-PONs by Wavelength Detuning and Phase-Modulation-Induced Spectral Broadening,” *IEEE Photonics Tech. Lett.*, vol. 19, no. 6, March 2007.

[38] F. Payoux *et al.*, “Gigabit Optical Access using WDM paN based on Spectrum Slicing and Reflective SOA,” *ECOC Proc.*, vol.3, pp. 455-459, 2005

[39] K. Iwatsuki *et al.*, “Access and Metro Networks Based on WDM Technologies,” *J. of Lightwave Tech.*, vol. 22, no. 11, Nov. 2004

[40] A. R. S. P. Shirazi *et al*, “Simulation and Analysis the Performance of 3970 Km DWDM Transmission Link Employing Optimized Semiconductor Optical Amplifiers,” *International J. of Commun. and Inform. Tech.*, vol. 1, no.1, Dec. 2011

[41] L. Deng *et al.,* “Intra and Inter-PON ONU to ONU Virtual Private Networking using OFDMA in a Ring Topology,” *IEEE Proc. On Meeting on Microwave Photonics,* pp. 176-179, Oct. 2011.

[42] U. H. Hong *et al.*, “Multi-Ring Architecture for Survivable WDM PON,” *IEEE Opto-Electronics and Commun. Conf.,*pp. 725-726, July 2012.

[43] M. I. Anis *et al.*, “Performance analysis of optical network based on OADM by using different filters,” International Conf, on Applicat. of Inform. and Commun. Tech.

[44] V. Bobrovs *et al.*, “Performance Improvement of High Speed Spectrum-Sliced Dense WDM-PON System,” *9th International Symposium on Telecommun.*, pp. 1-6, 2012.

[45] J. H. Lee *et al.*, “Extended-reach WDM-PON based on CW supercontinuum light source for colorless FP-LD based OLT and RSOA-based ONUs,” *J. of Optical Fiber Tech.*, vol. 15, no. 3, pp. 310-319, 2009.

[46] R. S. Kaler *et al.*, “Optimum algorithm for WDM channel allocation for reducing four-wave mixing effects,” *Optik*, pp. 898–904, 2008

[47] R.S. Kaler, Surinder Singh, “Simulation of DWDM signals using optimum span scheme with cascaded optimized semiconductor optical amplifiers,” *Optik* , pp. 74-82, 2003.

[48] R. S. Kaler *et al.*, “Wavelength Converter Using Semiconductor Optical Amplifier Mach-Zehnder Interferometer Based on XPM at 40 Gb/s for Future Transport Networks,” *Fiber and Integrated Optics*, vol. 28, no. 2, pp. 154-169, 2009

[49] R. S. Kaler, S. Singh, “Wide-Band Optical Wavelength Converter Based on Four-Wave Mixing Using Optimized Semiconductor Optical Amplifier,” *Fiber and Integrated Optics*, vol. 25, no. 3, pp. 213-230, 2006.

[50] F. J. Effenberger, H. Ichibangase, *et al.*, “Advances in broadband passive optical networking technologies,” *IEEE Commun. Mag.*, vol. 39, no. 12, pp. 118-122, 2001

[51] J. Segarra, V. Sales, J. Prat, “OLT design approach for resilient extended PON with OBS dynamic bandwidth allocation sharing the OLT optical resources”, in: *International Conference Transparent Optical Networks*, vol. 4, pp. 139–144, 2008

[52] Y. Cao, C. Gan, Y. Zhou, L. Shi, L. Zhu, “A novel architecture of reconfigurable WDM/TDM-PON”, *Wireless and Optical Communications Conference*, pp. 1–4, 2010

[53] C. Bock, J.A. Lazaro, J. Prat, “Extension of TDM-PON standards to a single-fiber ring access network featuring resilience and service overlay*”, J. Lightwave Technol.* vol. 25 pp. 1416–1421, 2007.

[54] Carlos Bock, Cristina Arellano, Josep Prat, “Resilient single-fiber ring access network using coupler-based OADMs and RSOA-based ONUs”, in: *Optical Fiber Communication Conference*, 2006 and *National Fiber Optic Engineers Conference,* 2006

[55] Fu-TaiAn, Kyeong Soo Kim, D. Gutierrez, S. Yam, E. Hu, K. Shrikhande, L.G. Kazovsky, “SUCCESS: a next-generation hybrid WDM/TDM optical access network architecture”, *J. Lightwave Technol.* vol. 22 pp. 2557–2569, 2004.

[56] Kazem A Sohraby, *et al.*, “Network Architecture for an All-Optica Internet”, *NFOEC Technical Proceedings*, Vol I, 27-31. Denver, CO, pp. 568-577, 2000

[57] G.P. Agrawal, Fiber Optic Communication Systems, John Wiley and Sons, New York, 1997.

[58] Marilet De Andrade, Anna Buttaboni, *et al.,* “Design of Long-Reach TDM/WDM Passive Optical Access Networks”, *Telecommunications Network Strategy and Planning Symposium (NETWORKS),* 2012

[59] L. R. Rabiner and B. Gold, The Theory and Application of Digital Signal Processing, Prentice-Hall, Englewood Cliffs, New Jersey, 1975

[60] Agrawal G. Fiber – Optic Communication Systems. – USA: John Wiley and Sons, pp. 561, 2002

[61] S.Dahlfort, “Comparison of 10 Gbit/s PON vs WDM-PON,” *ECOC*’, 2009.

[62] S. Singh and R.S. Kaler, “Placement of optimized semiconductor optical amplifier in fiber optical communication systems”, *Optik*, vol. 119, Issue 6, pp. 296‑302, 2008.

LIST OF PUBLICATIONS

[1] Komal Preet Kaur, R.S. Kaler, "Low Cost Architecture to Integrate Multiple PONs to a Spectrum Sliced WDM Network," Communicated to Optik